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DYNAMO-ELECTRIC
MACHINERY.

A SERIES OF LECTURES

BY

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WITH AN INTRODUCTION BY

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1883.

INTRODUCTION.

WHILE the Dynamo-Electric Machine has, within a comparatively short period, achieved a most wonderful development in connection with the rapidly increasing application of electricity to the useful arts, yet the essential principles of its construction and operation appear to be but imperfectly understood, even by otherwise well-informed electricians. The forms in which it has appeared have already become so numerous and varied, and the conditions of its construction and use are so complex in their mutual relations, as not only to defy all general methods of mathematical investigation, but to a considerable extent even satisfactory classification.

The great value of Professor Thompson's work, especially to the student and investigator, is mainly due to his masterly power of analysis, as shown in his method of logically grouping the various dynamos in connection with certain typical forms, each possessing characteristic individual elements, which are readily comprehended, and when once fixed in the mind, are instantly recognized wherever found. Hence, any existing machine, or any

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new machine which may hereafter appear, may be at once referred to its proper type, and the essential features of its organization compared with those of its rivals or predecessors.

The present series of lectures, like all the productions of its eminent author, are characterized not only by a thorough mastery of the subject, both in its theoretical and practical aspects, but by a felicity of classification, and a conciseness and clearness of statement and illustration, which literally leaves nothing to be desired. It forms a work which will be found alike indispensable to the educated electrician, the student, the inventor, and the intelligent mechanic or apprentice.

The correction of a few obvious, and unimportant errors, appearing in the text of the lectures, as originally published, and the insertion of a number of additional notes and references, by my associate, Mr. Howard R. Butler, and myself, will, it is hoped, add somewhat to the value of the work, especially to American readers. Such additions have been bracketed with the initials of the writers, in order that they may be distinguished from those of the author.

FRANK L. POPE.

ELIZABETH, N. J., May 10, 1883.

Dynamo-Electric Machinery.

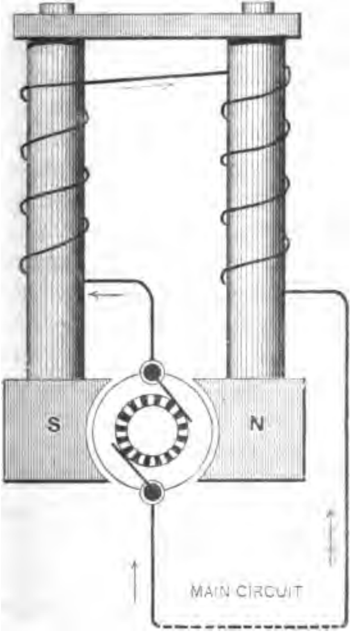
I.

THE DYNAMO IN THEORY.

By "Dynamo-electric Machinery," in the most general etymological sense of the term, is meant machinery for converting the energy of mechanical motion into the energy of electric currents, or *vice versa.* From this wide definition must be excepted machines like the well-known statical induction-machine of Holtz, whose action is purely electrostatic. Those machines only are included in the definition whose action is dependent on the principle of electro-magnetic induction, discovered by Faraday, in 1831. It is, however, not quite easy to decide what machines shall be called dynamo-electric machines, because the sense in which the term is used commonly is narrow, and restricted in a manner not quite logical.

The name dynamo-electric machine appears to have been first employed by Dr. Werner Siemens, in his communication of January 17th, 1867, to the Berlin Academy, in which he described a machine for generating electric currents by the application of mechanical power, the currents being induced in the coils of a rotating armature by the action of electro-magnets, which were themselves excited by the currents so generated. The machine was, in fact, a self-exciting dynamo, with the field magnets and armature united "in series" to the external circuit, or what we now call a "series-dynamo," a diagramatic representation of which is given in Fig. 1. But the term dynamo-electric machine, then introduced into electric technology, has not remained thus restrained to its narrowest meaning. It was next applied to machines of kindred nature, in which, though self-excited, only a portion of the entire current generated by the rotating armature was applied to excite the field-magnets (see Fig. 2). This principle of

Fig. 1.

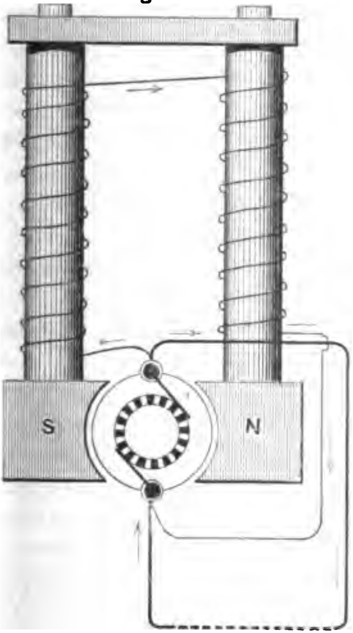


THE SERIES DYNAMO.

working (now known as that of the "shunt-dynamo"), first introduced by Wheatstone, is but a variation of the former arrangement in detail, and no violence is done to the original term to apply it to both cases. In fact, the name was welcomed as being convenient in practice for distinguishing such machines from those which were not self-excited—those in which either steel magnets or separately excited electro-magnets were used to produce the magnetic field.

But since the great development of electric lighting took place, it has been found convenient to use generating machines in certain combinations, in which the self-exciting principle is abandoned. Some systems of electric lights require alternating currents, produced in machines which cannot excite their own magnets with a continuous magnetization: and there are other systems where continuous currents are employed, in which also practice has shown that the currents are better regulated when the magnets of the dynamos are separately excited by currents derived from an external source. There is, then, a third class of dynamo-electric machine, the

Fig. 2.

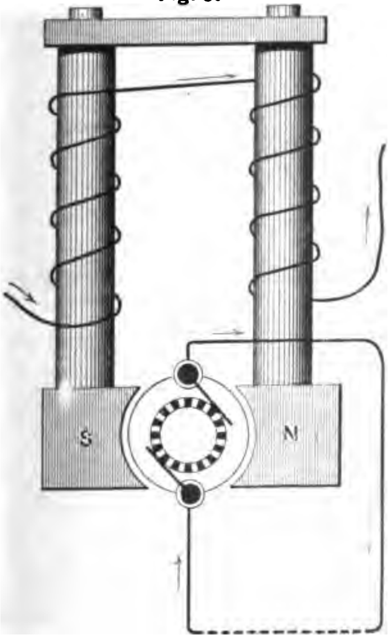


THE SHUNT DYNAMO.

"separately-excited dynamo" (Fig. 3), which was indeed earlier than either of the preceding, having been brought out by Wilde in 1866. A dynamo is a dynamo in fact, whether its magnets be excited by the whole of its own current, or by a part of its own current or by a current from an independent source. The source of the magnetizing power is indifferent, provided a magnetic "field" of sufficient intensity be produced wherein the generating coils can be rotated. Now, as it does not matter where the magnetizing power comes from, it is clear that we must include amongst possible sources the power of permanent steel magnets. In short, the arbitrary distinction between so-called magneto-electric mechines (see Fig. 4) and dynamo-electric machines fails when examined carefully. In all these machines a magnet, whether permanently excited, independently excited, or self-excited, is employed to provide a field of magnetic force. And in all of them dynamical power is employed to do the work of rotating the coils of the armature, in order to generate the electric currents.

The true and comprehensive definition

Fig. 3.



THE SEPARATELY-EXCITED DYNAMO.

of a dynamo-electric machine,. is then, the following: A dynamo-electric machine is a machine for converting energy in the form of dynamical power into energy in the form of electric currents, by the operation of setting conductors (usually in the form of coils of copper wire) to rotate in a magnetic field.

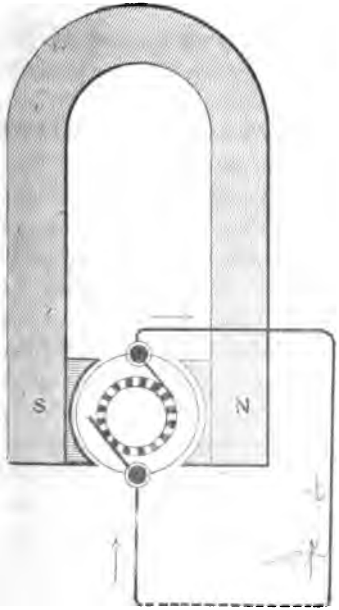
Inasmuch, however, as every dynamo-electric machine, in the most general sense of the term as now laid down, will work as a motor, and becomes a source of mechanical power when supplied with electric currents, it is possible to discuss dynamo-electric machinery from the opposite points of view in serving the two converse functions, in short, to treat the dynamo on the one hand as a generator, on the other hand as a motor.

It is as a generator only that the action of the dynamo will be considered in the first two of these lectures, reserving considerations respecting its functions as a motor for the third lecture of the present course.

THE DYNAMO IN THEORY.

To treat exhaustively the theory of dynamo-electric machines, would require not

Fig. 4.



THE MAGNETO DYNAMO.

one lecture, but many. It would be necessary, moreover, to enter upon lengthy mathematical and geometrical discussions, which would be out of place in the present course, which is expected to deal with subjects from an industrial, rather than from a purely scientific aspect. The mathematical theory of the dynamo is, indeed, very complex, and takes different forms for its expression in the four classes of machine now included under the one name of "dynamo." For every different variety in each of these classes, there is a fresh variety of mathematical symbols. The theory of alternate current machines is entirely different from that of machines which are to furnish continuous and constant currents. Every form of armature and coils requires its own specific treatment in symbols; and the simple consideration of putting iron cores into the coils, when treated mathematically, introduces such complex expressions as to yield no hopes of a satisfactory general solution.

The theory of the dynamo, then, which will be developed in the present lecture, will not be a general mathematical theory. The aim will be to deal with physical and experimental rather than mathematical ideas. A physical theory of the dynamo is not new, though none of great completeness has yet been given,* most of such explanations being devoted to single machines of some particular type.

It will here be my aim to develop a general physical theory, applicable to all the varied types of dynamo-electric machines, and to trace it out into a number of corollaries, bearing upon the construction of such machines. Having recited these consequences, which we shall deduce from theory, it will then remain to see how these consequences are verified and embodied in the various forms assumed by the dynamo in practice.

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* See Du Moncel (*Expose des Applications de l'Electricite*, vol. ii.); Niaudet, *Machines Electriques;* Schellen, *Die Magnet-und Dynamo-elektrischen Maschinen;* Antoine Breguet (see *Annales de Chimie et de Physique*, 1879). See also some theoretical papers by Clerk Maxwell in *Philosophical Magazine*, 1867, and by MM. Marcel Deprez, Cabanellas, de Gourant, and others in the *Comptes Rendus;* also sundry papers by Frölich, Werner Siemens, Hagenbach, and others in the *Elektrotechnische Zeitschrift*, and other German publications. Of more general scope is the physical theory advanced by the late M. Antoine Breguet, which deals with dyamos of the Gramme and Siemens type, and of which a detailed summary is given in Dredge's *Electric Illumination.* In an introductory chapter of the same work I have endeavored to lay the foundation of a more general physical throry. An admirable series of papers on the mathematical theory of dynamo-electric machines, from the pen of a well-known professor of physics, is at present appearing in the columns of *The Electrician.*

PHYSICAL THEORY OF DYNAMO-ELECTRIC MACHINES.

All dynamos are based upon the discovery made by Faraday in 1831, that electric currents are generated in conductors by moving them in a magnetic field. Faraday's principle may be enunciated as follows: When a conductor is moved in a field of magnetic force in any way so as to cut the lines of force, there is an electromotive force produced in the conductor, in a direction at right angles to the direction of the motion,* and at right angles also to the direction of the lines of force, and to the right of the lines of force, as viewed from the point from which the motion originates.*

---

* Or, more strictly, to the resolved part of the motion in a plane perpendicular to the lines of force.

This induced electromotive force is, as Faraday showed, proportional to the number of lines of magnetic force cut per second ; and is, therefore, proportional to the intensity of the magnetic "field," and to the length and velocity of the moving conductor. For steady currents, the flow of electricity in the conductor is, by Ohm's well-known law, directly proportional to this electromotive force, and inversely proportional to the resistance of the conductor. For sudden currents, or currents whose strength is varying rapidly, this is no longer true. And it is one of the most important matters, though one too often overlooked in the construction of dynamo-electric machinery, that the "resistance" of a coil of wire, or of a circuit, is by no means the only obstacle offered to the generation of a momentary current in that coil or circuit; but that, on the contrary, the self-induction exercised by one part of a coil or circuit upon another part or parts of the same, is, in many cases, quite as important a consideration, and in some cases a more important consideration, than the resistance.

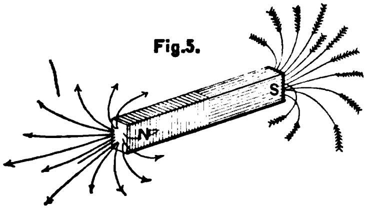
---

* A more usual rule for remembering the direction of the induced currents is the following adaptation from Ampère's well-known rule: Supposing a figure swimming in any conductor to turn so as to look along the (positive direction of the) lines of force. Then, if he and the conductor be moved towards his right hand, he will be swimming with the current induced by this motion.

To understand clearly Faraday's principle—that is to say, how it is that the act of moving a wire so as to cut magnetic lines of force can generate a current of electricity in that wire—let us inquire what a current of electricity is.

A wire through which a current of electricity is flowing looks no different from any other wire. No man has ever yet seen the electricity running along in a wire, or knows precisely what is happening there. Indeed, it is still a disputed point which way the electricity flows, or whether or not there are two currents flowing simultaneously in opposite directions. Until we know absolutely certainly what electricity is, we cannot expect to know precisely what a current of electricity is. But no electrician is in any doubt as to one most vital matter, namely, that when an electric current flows through a wire, the magnetic forces with which that wire is thereby, for the time, endowed, reside not in the wire at all, but in the space surrounding it. Every one knows that the space or "field" surrounding a magnet is full of magnetic "lines of force," and that these lines run

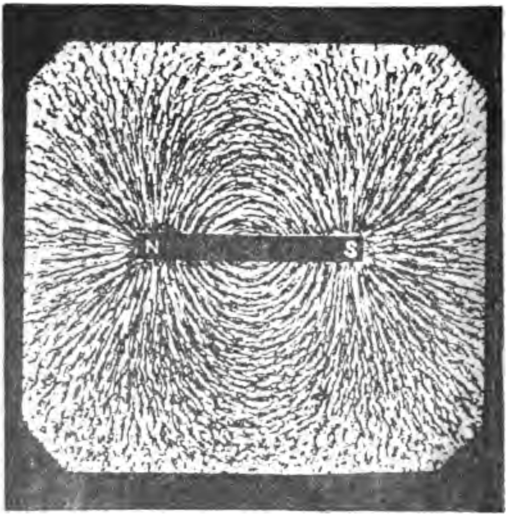
Fig. 5.



LINES OF FORCE OF BAR-MAGNET.

in tufts (Fig. 5) from the N-pointing pole to the S-pointing pole of the magnet, invisible until revealed by dusting iron filings into the field, whereby their presence is made known, though they are always in reality there (Fig. 6). A view of the magnetic field at the pole

Fig.6.

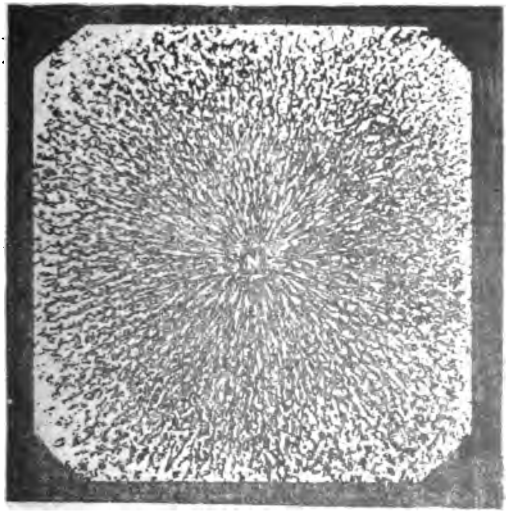


MAGNETIC FIELD OF BAR-MAGNET.

of a bar-magnet, as seen end-on, would of course exhibit merely radial lines, as in Fig. 7.

Now, every electric current (so-called) is surrounded by a magnetic field, the

Fig.7.

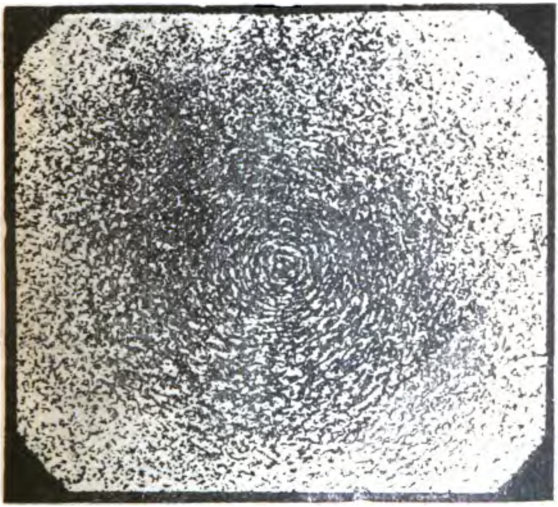


MAGNETIC FIELD ROUND ONE POLE, END-ON.

lines of which can be similarly revealed. To observe them, a hole is bored through a card or a piece of glass, and the wire which carries the current must be passed up through the hole. When iron filings are dusted into the field they assume the form of concentric circles (Fig. 8), showing that the lines of force run completely round the wire, and do not stand out in tufts. In fact, every conducting wire is surrounded by a sort of magnetic whirl, like that shown in Fig. 9. A great part of the energy of the so-called electric current in the wire consists in these external magnetic whirls. To set them up requires an expenditure of energy; and to maintain them requires also a constant expenditure of energy. It is these magnetic whirls which act on magnets, and cause them to set as galvanometer needles do, at right angles to the conducting wire.

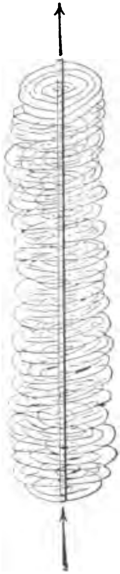
Now, Faraday's principle is nothing more nor less than this: That by moving a wire near a magnet, across a space in which there are magnetic lines, the motion of the wire, as it cuts across those magnetic lines, sets up magnetic whirls round the moving wire, or, in other language, generates a so-called current of electricity in that wire. Poking a magnet-pole into a loop or circuit of wire also necessarily generates a momentary current in the wire loop, because it mo-

Fig.8.



MAGNETIC FIELD SURROUNDING CURRENT.
THE CONDUCTING WIRE SEEN END ON.

Fig. 9.

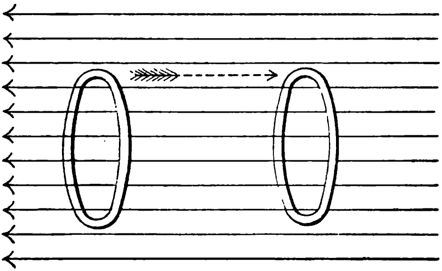


MAGNETIC WHIRL SURROUNDING WIRE CARRYING CURRENT.

mentarily sets up magnetic whirls. In Faraday's language, this action increases the number of magnetic lines of force intercepted by the circuit.

It is, however, necessary that the moving conductor should, in its motion, so cut the lines of force as to alter the number of lines of force that pass through the circuit of which the moving conductor forms part. If a conducting circuit

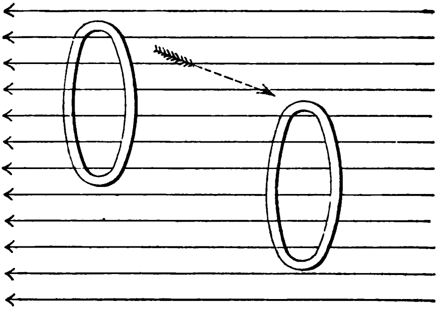
Fig. 10.



CIRCUIT MOVED WITHOUT CUTTING LINES OF FORCE OF UNIFORM MAGNETIC FIELD.

—a wire ring or single coil, for example—be moved along in a uniform magnetic field, as indicated in Fig. 10, so that only the same lines of force pass through it, no current will be generated. Or, if again, as in Fig. 11, the coil be moved, by a motion of translation, to another part of the uniform field, as many lines of force will be left behind as are gained in advancing from its first to its second position, and there will be no current generated in the coil. If the coil be merely rotated on

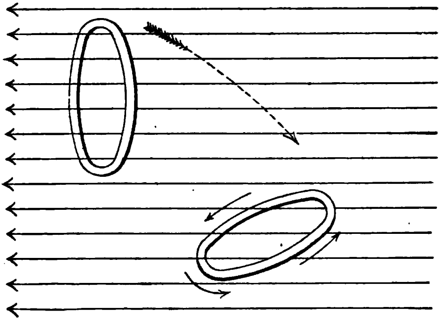
Fig. 11.



CIRCUIT MOVED WITHOUT CUTTING ANY MORE LINES OF FORCE.

itself round a central axis, like the rim of a fly-wheel, it will not cut any more lines of force than before, and this motion will generate no current. But if, as in Fig. 12, the coil be tilted in its motion across the uniform field, or rotated round any axis in its own plane, then the number of lines of force that traverse it will be altered, and currents will be generated. These currents will flow round the ring-coil in the positive* sense (as viewed from the point toward which the lines of force run), if the effect of the movement

Fig. 12.



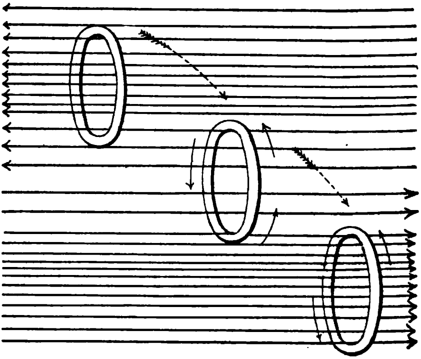
CIRCUIT MOVED SO AS TO ALTER NUMBER OF LINES OF FORCE THROUGH IT.

---

* The positive sense of motion round a circle is that opposite to the sense in which the hands of a clock go round.

is to diminish the number of lines of force that cross the coil; they will flow round in the opposite sense, if the effect of the movement is to increase the number of intercepted lines of force.

Fig. 13.



MOTION OF CIRCUIT IN NON-UNIFORM MAGNETIC FIELD.

If the field of force be not a uniform one, then the effect of taking the coil, by a simple motion of translation, from a place where the lines of force are dense to a place where they are less dense, as from position 1 to position 2 in Fig. 13, will be to generate currents. Or, if the motion be to a place where the lines of force run in the reverse direction, the effect will be the same, but even more powerful.

We may now summarize the points under consideration, and some of their immediate consequences, in the following manner:

(1.) A part, at least, of the energy of an electric current exists in the form of magnetic whirls in the space surrounding the conductor.

(2.) Currents can be generated in conductors by setting up magnetic whirls round them.

(3.) We can set up magnetic whirls in conductors by moving magnets near them, or moving them near magnets.

(4.) To set up and maintain such magnetic whirls uses up a continuous expenditure of energy, or, in other words, consumes power.

(5.) To induce currents in a conductor,

there must be relative motion between conductor and magnet of such a kind as to alter the number of lines of force embraced in the circuit.

(6.) Increase in the number of lines of force embraced by the circuit produces a current in the opposite sense to decrease.

(7.) Approach induces an electromotive force in the opposite direction to that induced by recession.

(8.) The more powerful the magnet pole or magnetic field, the stronger will be the current generated (other things being equal).

(9.) The more rapid the motion, the stronger will be the currents.

(10.) The greater the length of the moving conductor thus employed in cutting lines of force (*i.e.*, the longer the bars, or the more numerous the turns of the coil), the stronger will be the currents generated.

(11.) The shorter the length of those parts of the conductor not so employed, the stronger will be the current.

(12.) Approach being a finite process,

the method of approach and recession (of a coil towards and from a magnet-pole) must necessarily yield currents alternating in direction.

(13.) By using a suitable commutator, all the currents, direct or inversė, produced during recession or approach, can be turned into the same direction in the wire that goes to supply currents to the external circuits, thereby yielding an almost uniform current.

(14.) In a circuit where the flow of currents is steady* it makes no difference what kind of magnets are used to procure the requisite magnetic field, whether permanent steel magnets or electro-magnets, self-excited or otherwise.

(15.) Hence the current of the generator may be itself utilized to excite the magnetism of the field-magnets, by being caused, wholly or partially, to flow round the field magnet coils.

A very large number of dynamo-electric machines have been constructed upon the foregoing principles. The variety is indeed so great, that classification is not altogether easy. Some have attempted to classify dynamos according to certain constructional points, such as whether the machine did or did not contain iron in its moving parts (which is a mere accident of manufacture, since almost all dynamos will work either with or without iron in their armatures, though not equally well); or whether the currents generated were direct and continuous, or alternating (which is in many cases a mere question of arrangement of parts of the commutator or collectors); or what was the form of the rotating armature (which is, again, a matter of choice in construction, rather than of fundamental principle). The classification which I shall adopt, is one which I have found more satisfactory and fundamental than any other. I distinguish three genera or main classes of dynamos.

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* For currents that are not steady, there are other considerations to be taken into account, as will be shown hereafter.

Class I.—Dynamos in which there is rotation of a coil or coils in a uniform* field of force, such rotation being effected (as in the manner indicated in Fig. 12), round an axis in the plane of the coil, or one parallel to such an axis.

EXAMPLES.—Gramme, Siemens (Alteneck), Edison, Lontin, Bürgin, Fein, Schückert, Jürgensen, Weston (Thomson's Mousemill-dynamo).

Class II.—Dynamos in which there is translation† of coils to different parts of a complex field of varying strength, or of opposite sign. Most, but by no means all, of the machines of this class furnish alternate currents.

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* Or approximately uniform. A Gramme ring, or a Siemens drum armature, will work in a by no means uniform field, but is adapted to work in a field in which the lines of force run uniformly from one side to the other. But in such a field, a multipolar armature of many coils, such as that of Wilde, or such as is used in the Gramme alternate-current, or in the Siemens alternate-current machine, is useless and out of place. Indeed, the classification almost amounts to saying that in machines of Class I. there is one field of force, while in machines of Class II. there are many fields of force, or the whole field of force is complex.

† The motion by which the individual coils are carried round on such armatures as those of Niaudet, Wallace-Farmer, Siemens (alternate), &c., is, of course, not a pure translation. It may be regarded, however, as a combination of a motion of translation of the coil round the circumference of a circle, with a rotation of the coil round its own axis, which, as we have seen above, has *no* electrical effect. It is, of course, the translation of the coil to different parts of the field which is the effective motion.

Examples.—Pixii, Clarke, Niaudet, Wallace-Farmer, Wilde (alternate), Siemens (alternate), Hopkinson and Muirhead, Thomson (alternate), Gordon (alternate), Siemens-Alteneck (Disk Dynamo), Edison (Disk Dynamo), De Meritens.

Class III.—Dynamos having a conductor rotating so as to produce a continuous increase in the number of lines of force cut, by the device of sliding one part of the conductor on or round the magnet, or on some other part of the circuit.

Examples.—Faraday's Disk-machine, Siemens's ("Unipolar" Dynamo), Voice's Dynamo.

One machine, and one only, am I aware of which does not fall exactly within any of these classes,* and that is the extraordinary tentative dynamo of Edison, in which the coils are waved to and fro at the ends of a gigantic tuning-fork, instead of being rotated on a spindle.*

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* There are a few dynamos, including the Elphinstone Vincent, and the four pole Gülcher, which, though really belonging to the first class, are not named above, because they are, in reality, compound

Suppose, then, it were determined to construct a dynamo upon any one of these plans—say the first—a very slight acquaintance with Faraday's principle and its corollaries would suggest that, to obtain powerful electric currents, the machine must be constructed upon the following guiding lines:—

(*a.*) The field-magnets should be as strong as possible, and their poles as near together as possible.

(*b.*) The armature should have the greatest possible length of wire upon its coils.

---

machines. The Gülcher, with its doubled field magnets and four collecting brushes, is really a double machine, though it has but one rotating ring. The same is the case with an octagonal pattern Gramme, which has four brushes. The Elphinstone-Vincent machine, a remarkable one in many respects, is a triple machine, having six brushes; and may, indeed, be used as three machines, to feed three separate circuits.

[* This curious invention is described in Edison's patent, No. 218,166, of Sept 9, 1879.]

(*c*.) The wire of the armature coils should be as thick as possible,so as to offer little resistance.

(*d*.) A very powerful steam-engine should be used to turn the armature, because,

(*e*.) The speed of rotation should be as great as possible.

Unfortunately, it is impossible to realize all these conditions at once, as they are incompatible with one another; and, moreover, there are a great many additional conditions to be observed in the construction of a successful dynamo. We will deal with the various matters in order, beginning with the speed of the machine.

Relation of Speed to Power.

Theory shows that, if the intensity of the magnetic field be constant, the electromotive force should be proportioned to the speed of the machine. Numerous experiments, by many different workers, have shown that this is true, within certain limits, for those machines in which the field magnets are independent of the main circuit, that is to say, for magneto and separately excited dynamos. It is not, however, quite exact unless the resistance of the circuit be increased proportionately to the speed, because the current in the coils itself re-acts on the magnetic field, and alters the distribution of the lines of force. The consequence of this reaction is that, firstly, the position of the "diameter of commutation" is altered; and, secondly, the effective number of lines of force is reduced. So that, with a constant resistance in circuit, the electromotive force, and therefore the current, are slightly less at high speeds than the proportion of the velocities would lead one to expect. Since the product of current into electromotive force gives a number proportional to the electric work of the machine, it follows that, for "independently excited" machines, the electric work done in given time is nearly proportional to the square of the speed, and the work drawn from the steam-engine will be similarly proportional to the square of the speed.

In self-exciting machines, whether "series" or "shunt" in their arrangements, a wholly different law obtains. If the iron of the field-magnets be not magnetized near to saturation, then, since the increase of current consequent on increase of speed produces a nearly proportional increase in the strength of the magnetic field, this increase will re-act on the electromotive force, and cause it to be proportional more nearly to the square of the velocity, which again will cause the current to increase in like proportion. But since the magnetization of the iron is, even when far from saturation point, not exactly proportional to the magnetizing force, but something less, it is in practice found that the electric work of the machine is not proportional to the fourth power of the speed, is not even proportional to the third power of the speed, but to something slightly less than the latter.

As mechanical considerations forbid too high a velocity in the moving parts, it is clear that, if there be a limiting speed at which it is safe to run any given armature, the greatest amount of work will be done at that speed by using the most powerful magnets possible, namely, electro-magnets rather than magnets of steel.

Marcel Deprez has shown* that it is convenient to study the action of dynamos, by constructing a curve which he calls a "characteristic," showing, for any given speed, the relation between electromotive force and strength of current generated in a circuit of given resistance. Amongst other conclusions, M. Deprez has found that for every dynamo there is a certain speed which we may call the "critical speed," at which, no matter what the current is which circulates in the coils of the field magnets, the electromotive force is proportional to the strength of that current; and he bases upon the discovery of this critical speed two methods of utmost importance in practice, for obtaining, automatically, either a constant electromotive force or a constant current at will, in a circuit in which the resistances are varied to any degree.

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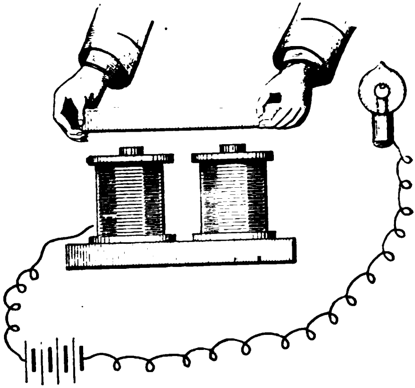
* *Comptes Rendus*, 1881, and elsewhere. For an excellent summary of the work of M. Deprez, see *La Lumiere Electrique*, February 18, 1882.

In all these combinations, however, everything depends upon the condition that the driving speed shall be uniform. For all the best kind of electric work, a gas-engine is wholly out of the question as a source of power, because of its extreme inequalities in speed. Even with the best steam-engines, a specially sensitive valve is required; and probably such valves will, in the future, be operated electrically by self-acting electro-magnet gearing. In any case, where the driving is at all liable to be uneven, the obvious and simple precaution should be taken of placing a heavy fly-wheel on the axis of the dynamo. It is, indeed, singular that this is not more generally done.

FIELD-MAGNETS.

The coils of the field-magnets of a dynamo cannot be constructed of no resistance. They, therefore, always waste some of the energy of the currents in heat. It has, therefore, been argued that it cannot be economical to use electro-magnets in comparison with permanent magnets of steel, which have only to be magnetized once for all. Nevertheless, there are certain considerations which tell in favor of electro-magnets. For equal power, their prime cost is less than that of steel magnets, which, moreover, are not permanent, but require remagnetizing at intervals. Moreover, as we have seen, from the fact that there is a limiting velocity at which it is safe to run a machine, it is important, in order not to have machines of needlessly great size, to use the most powerful field-magnets possible. But if we do not get our magnetism for nothing, and find it more convenient to spend part of our current upon the electro-magnets, economy dictates that we should so construct them that their magnetism may cost us as little as possible. To magnetize a piece of iron requires the expenditure of energy; but when once it is magnetized, it requires no further expenditure of energy (save the slight loss by heating in the coils, which may be reduced by making the resistance of the coils as little as possible) to keep it so magnetized, provided the magnet is doing no work. Even if it be doing no work, if the current flowing round it be not steady, there will be loss. If it do work, say in attracting a piece of iron to it, then there is an immediate and corresponding call upon the strength of the current in the coils, to provide the needful energy. This point may be illustrated by the following experiment:—Let a current from a steady source (see Fig. 14) pass through an incandescent lamp, and also through an electro-magnet, whose cores it magnetizes. When once established, the current is perfectly steady, and none of its energy is wasted on the magnet (save the negligible trifle due to the resistance of the coils). But if now the magnet is allowed to do work in attracting an iron bar towards itself, the light of the lamp is seen momentarily to fade. When the iron bar is snatched away, the light exhibits a momentary increase; in each case resuming its original intensity when the motion ceases. Now,

Fig. 14.



REACTION OF MOVING MASS OF IRON ON AN ELECTRO-MAGNET.

in a dynamo where, in many cases there are revolving parts containing iron, it is of importance that the approach of a recession of the iron parts should not produce such reactions as these in the magnetism of the magnet. Large, slow-acting field-magnets are therefore advisable. The following points embody the conditions for attaining the end desired.

(*a.*) The body of the field-magnets should be solid. Even in the iron itself currents are induced, and circulate round and round whenever the strength of the magnetism is altered. These self-induced currents tend to retard all changes in the degree of magnetization. They are stronger in proportion to the square of the diameter of the magnet, if cylindrical or to its area of cross-section. A thick magnet will, therefore, be a slow-acting one, and will steady the current induced in its field.

(*b.*) Use magnets having in them plenty of iron. It is important to have a sufficient mass, that saturation may not be too soon attained.

(*c.*) Use the softest possible iron for field-magnets, not because soft iron magnetizes and demagnetizes quicker than other iron (that is here no advantage); but because soft iron has a higher magnetic susceptibility than other iron—is not so soon saturated.

(*d.*) Use long magnets. Again, the use of long magnets is to steady the magnetism, and therefore to steady the current. A long magnet takes a longer time than a short magnet to magnetize and demagnetize. It costs more than a short magnet, it is true, and requires more copper wire in the exterior coil; but the copper wire may be made thicker in proportion, and will offer less resistance. The magnetism so obtained should be utilized as directly as possible, therefore

(*e.*) Place the field-magnets or their pole-pieces as close to the rotating armature as is compatible with safety in running.

(*f.*) Avoid edges and corners on the magnets and pole-pieces if you want a uniform field. The laws of distribution of the magnetic lines of force round a pole are strikingly akin to those of the distribution of electrification over a conductor. We avoid edges and points in the latter case, and ought to do so in the former. If the field-magnets or their pole-pieces have sharp edges, the field cannot be uniform, and some of the lines of force will run uselessly through the space outside the armature instead of going through it. Theoretically, the very best form to give externally to a magnet is that of the curves of the magnetic lines of force.

(*g*.) Reinforce the magnetic field by placing iron, or better still, electro-magnets, within the rotating armature. In many cases this is done by giving the armature coils iron cores which rotate with them; in other cases, the iron cores or internal masses are stationary. In the former case there is loss by heating; in the latter, there are structural difficulties to be overcome. Siemens has employed a stationary mass within his rotating drum-armature. Internal electro-magnets serving the function of concentrating the magnetism of the field, and of so providing a continuous magnetic circuit, have been used by Lord Elphinstone and Mr. Vincent. A similar device obtains in Sir. W. Thomson's "mouse-mill" dynamo, and in Jürgensen's dynamo.

(*h.*) In cases where a uniform magnetic field is not desired, but where, as in dynamos of the second class, the field must have varying intensity at different points, it may be advisable specially to use field-magnets with edges or points, so as to concentrate the field at certain regions.

POLE-PIECES.

(*i.*) The pole-pieces should be heavy, with plenty of iron in them, for reasons similar to those urged above.

(*j.*) The pole-pieces should be of shapes really adapted to their functions. If intended to form a single approximately uniform field, they should not extend too far on each side. The distribution of the electromotive force in the various sections of the coils on the armature depends very greatly on the shape of the pole-pieces.

(*k.*) Pole-pieces should be constructed so as to avoid, if possible, the generation in them of useless Foucault currents.* The only way of diminishing loss from this source is to construct them of laminæ, built up so that the mass of iron is divided by planes in a direction perpendicular to the direction of the currents, or of the electromotive forces tending to start such currents.

(*l.*) If the bed-plates of dynamos are of cast-iron, care should be taken that these bed-plates do not short-circuit the magnetic lines of force from pole to pole of the field-magnets. Masses of brass, zinc, or other non-magnetic metal may be

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[* The term Foucault currents has been applied to those currents which are induced within a solid mass or plate of metal when moved or rotated in a magnetic field, or when stationed in the vicinity of a moving magnet. The energy of such currents expends itself either in raising the temperature of the mass or in stopping the motion which established the currents.]

interposed; but are at best a poor resource. In a well-designed dynamo, there should be no need of such devices.

FIELD-MAGNET COILS.

(*m.*) In order to be of the greatest possible service, the coils of the field-magnets should be wound on most thickly at the middle of the magnet, not distributed uniformly along its length, nor yet crowded about its poles. The reason for this is two-fold. Inspection of Fig. 6, will show that many of the lines of force of a magnet "leak out" from the sides of the magnet before reaching its poles, where they should all emerge if the mass of the magnet were perfectly equally magnetized throughout its whole length. Internally, the magnetization of the magnet is greatest at its center. At, or near the center, therefore, place the magnetizing coils, that the lines of force due to them may run through as much iron as possible. The second reason for not placing the coils at the end is this: any external influence which may disturb the magnetism of a magnet, or affect the distribution of its lines of force, affects the lines of force in the neighborhood of the pole far more than those in any other region. It is for this reason that in Bell's telephones, where it is desired to make a magnet most sensitive to variations in intensity, the coils are fixed on at the pole. In the field-magnet of a dynamo, on the contrary, where the magnet is wanted to be as steady and constant as possible in its magnetic power, the coils should not be placed on the poles.

(*n.*) The proper resistances to give to the field-magnet coils of dynamos have been calculated by Sir William Thomson,* who has given the following results:

For "series dynamo," make the resistance of the field magnets a little less than that of the armature. Both of them should be small, compared with the resistance of the external circuit. The ratio of the waste by heating in the machine, to the total electric work of the machine, will be:

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* British Association Report, 1881, p. 528.

$$\frac{\text{waste:}}{\text{total work}}=\frac{R_M+R_A}{R_M+R_A+R_X}$$

and

$$\frac{\text{useful work}}{\text{total work}}=\frac{R_X}{R_M+R_A+R_X}$$

where

R_M is the resistance of the magnets,
R_A " " " armature,
R_X " " " external circuit.

For a "shunt dynamo," the rule is different. The best proportions are when such that

$$R_X=\sqrt{R_M\ R_A},$$

or that

$$R_M=\frac{R_X^2}{R_A};$$

also the ratio of useful work is:

$$\frac{\text{useful work}}{\text{total work}}=\frac{1}{1+2\sqrt{\frac{R_A}{R_M}}}.$$

An example of the latter may be of advantage. Suppose it was wished that the waste should not be more than 10 per cent. of the useful work, the ratio of the formula must equal $\frac{10}{11}$, or $1 \div 1\frac{1}{10}$ Hence $\sqrt{\frac{R_A}{R_M}}$ must equal $\frac{1}{20}$; or R_M the resistance of the field magnets must be 400 times R_A that of the armature.

ARMATURE CORES.

(*o.*) Theory dictates that if iron is employed in armatures, it must be slit or laminated, so as to prevent the generation of Foucault currents.* Such iron cores should be structurally divided in planes normal to the circuits round which electromotive force is induced; or should be divided in planes parallel to the lines of force and to the direction of the motion. Cores built up of varnished iron wire, or of thin disks of sheet-iron separated by varnish, asbestos paper, or mica, partially realize the required condition.

(*p.*) Armature cores should be so arranged that the direction of polarity of their magnetization is never abruptly reversed during their rotation. If this precaution is neglected, the cores will be heated.

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* See note *ante.*

ARMATURE COILS.

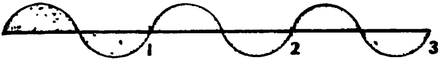
(*q*.) All needless resistance should be avoided in armature coils, as hurtful to the efficiency of the machine. The wires should therefore be as short and as thick as is consistent with obtaining the requisite electromotive force, without requiring an undue speed of driving.

(*r*.) The wire should be of the very best electric conductivity. The conductivity of good copper is so nearly equal to that of silver (over 96 per cent.), that it is not worth while to use silver wires in the armature coils of dynamos.

(*s*.) In cases where rods or strips of copper are used instead of mere wires, care must be taken to avoid Foucault currents by laminating such conductors, or slitting them in planes parallel to the electromotive force, that is to say, in planes perpendicular to the lines of force, and to the direction of the rotation.*

(*t*.) In dynamos of the first class, when used to generate currents in one direction, since the currents generated in the coils are doing half their motion inverse to those generated during the other half of their motion, a commutator or a collector of some kind must be used. In any single coil without a commutator, the alternate currents would be generated in successive revolutions, if the coil were destitute of self-induction currents, whose variations may be graphically expressed by a recurring sinusoidal curve, such as Fig. 15. But if by the addition of a sim-

Fig. 15.



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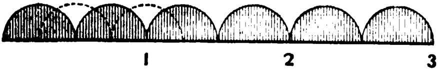
* It will be observed that the rule for eliminating Foucault currents is different, in the three cases, for magnets and their pole-pieces, for moving iron armature cores, and for moving conductors in the armature.

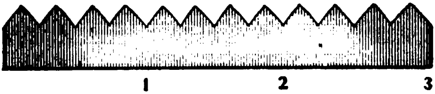
ple split-tube commutator the alternate halves of these currents are reversed, so as to rectify their direction through the rest of the circuit, the resultant currents will not be continuous, but will be of one sign only, as shown in Fig. 16, there being two currents generated during each revolution of the coil. If two coils are used, at right angles to each others'

Fig. 16.



planes, so that one comes into the position of best action. while the other is in the position of least action (one being normal to the lines of force, when the other is parallel to them), and their actions be superposed, the result will be, as shown in Fig. 17, to give a current which is continuous, but not steady, having four slight undulations per revolution. If any number of separate coils are used, and their effects, occurring at regular intervals, be superposed, a similar curve will be obtained, but with summits proportionately more numerous and less elevated. When the number of coils used is very great, and the overlappings of the curves still more complete, the row of summits will form practically a straight line, or the whole current will be practically constant.

Fig. 17.



(*u.*) The rotating armature coils ought therefore to be divided into a large number of sections, each coming in regular succession into the position of best action.

(*v.*) If these sections, or coils, are independent of each other, each coil, or diametral pair of coils, must have its own commutator. If they are not independent, but are wound on in continuous connection all round the armature, a collector is needed, consisting of parallel metallic bars as numerous as the sections each bar communicating with the end of one section and the beginning of the next.

(*w.*) In any case, the connections of such sections and of the commutators, or collectors, should be symmetrical round the axis; for if not symmetrical, the induction will be unequal in the parts that successively occupy the same positions with respect to the field-magnets, giving rise to inequalities in the electromotive force, sparking at the commutator, or collector, and other irregularities.

(*x.*) In the case where the coils are working in series, it is advantageous to arrange the commutator to cut out the coil that is in the position of least action, as the circuit is thereby relieved of the resistance of an idle coil. But no such coil should be short-circuited to cut it out. In the case where the coils are working in parallel, cutting out an idle coil increases the resistance, but may be advisable to prevent heating from waste currents traversing it from the active coils.

(*y.*) In the case of pole-armatures, the coils should be wound on the poles rather than on the middles of the projecting cores; since the variations in the induced magnetism are most effective at or near the poles. (See § *m.*)

(*z.*) Since it is impossible to reduce the resistance of the armature coils to zero, it is impossible to prevent heat being developed in those coils during their rotation; hence it is advisable that the coils should be wound with air spaces in some way between them, that they may be cooled by ventilation.

(*aa.*) The insulation of the armature coils should be ensured with particular care, and should be carried out as far as possible with mica and asbestos, or other materials not liable to be melted if the armature coils become heated.

COMMUTATORS, COLLECTORS, AND BRUSHES.

(*ab.*) Commutators and collectors being liable to be heated through imperfect contact, and liable to be corroded by sparking, should be made of very substantial pieces of copper.

(*ac.*) In the case of a collector made of parallel bars of copper, ranged upon the periphery of a cylinder, the separate bars should be capable of being removable singly, to admit of repairs and examination.

(*ad.*) The brushes should touch the commutator or the collector at the two points, the potentials of which are respectively the highest and the lowest of all the circumference. In a properly and symmetrically built dynamo, these points will be at opposite ends of a diameter.

(*ae.*) In consequence of the armature itself, when traversed by the currents, acting as a magnet, the magnetic lines of force of the field will not run straight across, from pole to pole, of the field magnets, but will take, on the whole, an angular position, being twisted a considerable number of degrees in the direction of the rotation. Hence the diameter of commutation (which is at right-angles to the resultant lines of force in machines of the

Siemens and Gramme type, and parallel to the resultant lines of force in machines of the Brush type), will be shifted forward. In other words, the brushes will have a certain angular lead. The amount of this lead depends upon the relation between the intensity of the magnetic field and the strength of the current in the armature. This relation varies in the four different types of field magnets. In the series dynamo, where the one depends directly on the other, the angle of lead is nearly constant, whatever the external resistance. In other forms of dynamo, the lead will not be the same, because the variations of resistance in the external circuit do not produce a proportionate variation between the two variables which determine the angle of lead.

(*af.*) Hence in all dynamos it is advisable to have an adjustment, enabling the brushes to be rotated round the commutator or collector, to the position of the diameter of commutation for the time being. Otherwise there will be sparking at the brushes, and in part of the coils at least the current will be wasting itself by running against an opposing electromotive force.

(*ag.*) The arrangements of the collector, or commutator, should be such that, as the brushes slip from one part to the next, no coil or section in which there is an electromotive force should be short circuited, otherwise work will be lost in heating that coil. For this reason, it is well so to arrange the pole places that the several sections or coils on either side of the neutral position should differ but very slightly in potential from one another.

(*ah.*) The number of contact points between the brushes and the collector, or commutator, should be as numerous as possible, for by increasing the number of contacts, the energy wasted in sparks will be diminished inversely as the square of that number. The brushes might, with advantage, be laminated, or made of parallel loose strips of copper, each bearing edgeways on the collector.

RELATION OF SIZE TO EFFICIENCY.

The efficiency of a dynamo electric machine is the ratio of the useful electrical work done by the machine to the total mechanical work applied in driving it. Every circumstance which contributes to wasting the energy of the current reduces the efficiency of the machine. In the preceding paragraphs it has been shown what the chief electric sources of waste are, and how they may be avoided. The precautions needful to obviate Foucault currents, to avoid reversals of magnetization, to get rid of needless resistance, to obviate opposing electro motive forces, have been detailed. Mechanical friction of the moving parts can be minimized also by due mechanical arrangements. But one thing cannot be entirely obviated, because even the best conductors employed have a certain resistance. We cannot prevent the heating of the conducting coils; and the more powerful the current generated by the machine, the more important does this source of waste become.

There is but one way to reduce this, and that is by increasing the size of the machines. For some three years or so I have been the advocate of large dynamo machines, not because I have any admiration for mere bigness, but because, as in steam engines so in dynamos, the larger machines may be made more efficient than the small, in proportion to their cost. In discussing the relation of size to efficiency, I shall assume, for the sake of argument, that the size of any machine can be increased n times in every dimension, and that though the dimensions are increased, the velocity of rotation remains the same, and that the intensity of the magnetic field, per square centimeter, remains also constant. If the linear dimensions be n times as great in the larger machine as in the smaller, the area it stands on will be increased n^2 times, and its volume and weight n^3 times. The cost will be less than n^3 times but greater than n times. If the same increase of dimensions in the coils be observed (the number of layers and of turns remaining the same as before), there will be in the armature coils a length n times as great, and the area of cross-section of the wire will be n^2 times as great as before. The resistance of these coils will, therefore, be but $\frac{1}{n}$ part of the original resistance of the smaller machine. If the field-magnet coils are increased similarly they will offer only $\frac{1}{n}$ of the resistance of those of the smaller machine. Moreover, seeing that while the speed of the machine is the same, the area cut through by the rotating coils is increased n^2 times, these coils will in the same time cut n^2 times as many lines of force, or the electromotive force will be increased n^2 times. Supposing the whole of the circuit to be similarly magnified, its resistance will also be but $\frac{1}{n}$ of the previous value.

If the machine is a "series"-wound dynamo, an electromotive force, n^2, working through $\frac{1}{n}$ resistance will give a current n^3 times as great as before. Such a current will, as a matter of fact, much more than suffice to bring the magnetic field to the required strength, viz., n^2 times the area of surface magnetized to the same average intensity per square centimeter, as stipulated; for the mass of iron being n^3 times as great, it need not be so much saturated as before to give the required field. Here an economy may be effected, therefore, by further reducing the number of coils, and therefore the wasteful resistance of the field-magnet coils, in the proportion of n^3 to n^2, or to $\frac{1}{n}$ of its already diminished value. Even if this were not done, by the formula given above for the electrical efficiency of a "series" dynamo, the waste, when working through a constant external resistance, will be n-fold less than with the smaller machine. Now, if the current be increased n^3 times, and the electromotive force n^2 times, the total electric work which is the product of these will be n^5 times greater than in the small machine, and it will consume n^5 times as much power to drive it.* It is clearly an important economy, if a machine costing

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* This calculation agrees with the result deduced on entirely different principles by M. Marcel Deprez, M. Deprez considers the mutual reaction, dF, between two elements, ds and ds', of a system of conductors which, by Ampère's principle, is

$$dF = C^2 \frac{ds\, ds'}{r^2} f\,(a)$$

where C is the current, r the distance of the elements apart, and $f\,(a)$ a certain function of the machine, independent of its size. Writing a for the area, we have

$$dF = \frac{C^2}{a^2} \cdot \frac{a ds\,.\,a ds'}{r^2} \cdot f\,(a)$$
$$= \frac{C^2}{a^2} \cdot \frac{dv\,.\,dv'}{r^2} \cdot f\,(a)$$

which, if the linear dimensions be increased n times, becomes

$$dF' = \frac{C^2}{a^2} \cdot \frac{n^3 dv\,.\,n^3 dv'}{n^2 r^2} \cdot f\,(a)$$
$$= n^4 dF$$

whence, since this is true for all elements of the circuits, $\frac{F'}{F} = n^4$, which is Deprez's so-called "law of similars," which asserts that for similar machines the "statical effort" increase as the fourth power of the linear dimensions. But work W=F × distance, and, in the similar machine whose dimensions are increased n times, the available distance through which the force F′ can act also n times grealer.

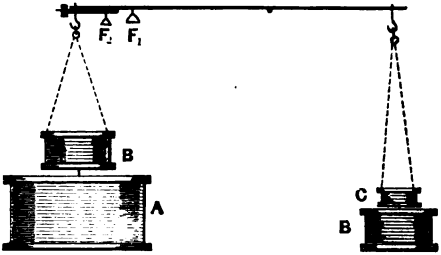
Hence $\frac{W'}{W} = n^5$, as above.

less than n^3 times as much, will do n^5 times as much work (to say nothing of the increased ratio of efficiency). A machine doubled in all its linear dimensions will not cost eight times as much, and will be electrically thirty-two times as powerful a machine.

Suppose the machine to be "shunt" wound, then to produce the field of force of n^2 times as many square centimeters area, will require (if the electromotive force be n^2 times as great) that the absolute strength of the current remain the same as before in the field-magnet coils. This can be done by using the same sized wire as before, and increasing its length n^2 times, to allow for n times as many turns, of n times as great a diameter each, in the same number of layers of coils as before. In this case the work done in the shunt being equal to the product of the n^2-fold electromotive force into the unaltered current will be only n^2 times as great, while the whole work of the machine is augmented n^5 times. Now, if while augmenting the total work

n^5 times, we have increased the waste work not to n^5 times but only n^2 times, it is clear that the ratio of waste to the total effect is diminished n^3-fold. There is therefore, every reason to construct large machines, from the advantage of economy, both in relative prime cost and relative efficiency.

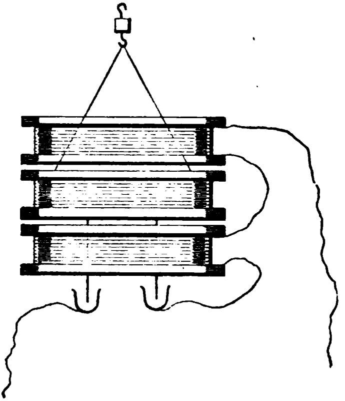
Fig. 18.



S. P. THOMPSON'S EXPERIMENTAL BALANCE.

Being desirous of testing the correctness of the deduction that the working capacity of a machine of n-fold linear dimensions is n^5 times as great, I constructed a little instrument, of which a drawing is given in Fig. 18. In this instrument there are two pairs of coils, that on the left being, in every way, the counterpart of that on the right, but of double linear dimensions. When all four coils were traversed by the same current, the point of equilibrium was $\frac{1}{17}$ of the length of the beam from the extremity; or the attraction of the larger system was sixteen times that of the smaller. Now, it is clear that the larger force can be exerted through double the distance, or that the work-power is 32-fold, and 32 is 2^5, as theory requires. After I had constructed my apparatus, I learned that M. Marcel Deprez had made a very similar arrangement, but without the beam, to prove that the statical forces of similar machines are (see foot-note *ante*) proportional to the fourth power of the linear dimensions. M. Deprez's instrument consisted of a modified Mascart's electro-dynamometer, having a coil suspended from a balance, and acted upon by two others, placed axially above and below it (see Fig. 19). The force was measured by directly balancing it against weights. Two such arrangements were made, one double the size of the other, and when equal currents were sent through them, M. Deprez found the forces to be as 5.600 to 0.355 kilos., or almost exactly 16 to 1.

Fig. 19.



MARCEL DEPREZ'S ELECTRO-DYNAMIC BALANCE.

METHODS OF EXCITING THE FIELD MAGNETISM.

It only remains to develop certain theoretical considerations respecting the method of exciting the magnetism of the field in which the armatures are to revolve. The four main methods have already been alluded to at the outset of this lecture; but nothing has been said about the advantages or disadvantages of the four systems.

Magneto-Dynamos.—The magneto-dynamos (Fig. 4.) have the advantage, in theory at least, that their electromotive force is very nearly exactly proportional to the velocity of rotation; though, of course, the variable difference of potential between the terminals of the circuit will depend on the relation of the resistance of the external circuit to the internal resistance of the armature coils. They possess the disadvantage that, since steel cannot be permanently magnetized to the same degree as that which soft iron can temporarily attain, they are not so powerful as other dynamos of equal size.

Separately-Excited Dynamos. — The separately excited dynamo (Fig. 3,) has the same advantage as the magneto-machine, in its electromotive force being independent of accidental changes of resistance in the working circuit, but it is more powerful. It has, moreover, the further advantage that the strength of the field is under control, for by varying either the electromotive force or the resistance in the exciting circuit, the strength of the magnetic field is varied at will. It has the disadvantage of requiring a separate exciting machine.

Series Dynamos.—The ordinary, or series dynamo (Fig. 1), is usually a cheaper machine, for equal power, than any of the other forms, as its coils are simpler to make than those of a shunt machine, and it wants no auxiliary exciter. It has the disadvantage of not starting action until a certain speed has been attained, or unless the resistance of the circuit is below a certain minimum. It is also liable to become reversed in polarity, a serious disadvantage when this machine is applied for electro-plating or for charging accumulators.*

From its arrangement, it is clear that any increase of the resistance in the circuit lessens its power by diminishing the strength of its magnetic field. Hence it is better adapted for use with lamps arranged in parallel arc than for lamps arranged in series. An additional lamp switched in, in series, adds to the resistance of the circuit, and diminishes the power of the machine to supply current, while on the other hand, an additional lamp in parallel reduces the total resistance offered by the network of the circuit, and adds to the power of the machine to provide the needed current. It is easy to regulate the currents given by a series dynamo, by introducing a shunt of variable resistance across the field-magnet, thus

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[* This difficulty is avoided in practice by making a portion of the field magnet of hardened steel, or by means of an automatic shunting device for cutting off the current due to the opposing electro-motive force of the electrolytic cell. See patents of H. J. Smith, No. 173,682, Feb. 16, 1876; and E. Weston, No. 182,977, Oct. 3, 1877; reissue 8102, Feb. 25, 1878.—P.]

altering the magnetizing influence of the current.

Shunt Dynamos.—The shunt dynamo (Fig. 2,) has several advantages over other forms. It is less liable to reverse its polarity than the series dynamo, and it is commonly considered as providing the magnetizing power to the magnets with less waste of current. Moreover, for a set of lamps in series, its power to supply the needful current increases with the demands of the circuit, since any added resistance sends additional current round the shunt in which the field-magnets are placed, and so makes the magnetic field more intense. On the other hand, there is a greater sensitiveness to inequalities of driving in consequence of the great self-induction in the shunt. As previously pointed out, when there are sudden changes in the electromotive force acting in a complex circuit, the momentary currents thus set up do not distribute themselves in the various parts of the circuit in the simple inverse ratio of the resistances, for their distribution depends also, and in some cases chiefly, upon the self-induction in the various parts. It is more difficult to set up a sudden current in a circuit whose self-induction is great (or which, for example, consists of many turns wound closely together, so that they exercise great inductive action on each other, especially if they be wound about an iron core), than in one in which the self-induction is small. We cannot here follow further the mathematical law of the action of self-induction on momentary changes of electromotive force. But the application to the shunt-wound dynamo is too important to be passed over.

Any of these systems may be applied either in direct current or in alternate-current machines. Each of these four systems of exciting the field magnetism has its own merits for special cases, but neither of them is perfect. Not one of these methods will insure that, with a uniform speed of driving, either the electromotive force or the current shall be constant, however the resistances of the circuit are altered.

But, though theory tells us that neither of these systems is perfect, theory does not leave us without a guide. Thanks to the genius of M. Marcel Deprez, we have been taught how to combine these methods so as to secure in practice a machine which shall, when driven at a constant speed, give either a constant electromotive force or a constant resistance. A consideration of the various methods of combining the four systems of exciting the field-magnetism is reserved for the lecture on the dynamo in practice.

Meantime, it may safely be said that there is no such thing yet as a best dynamo. As with the different kinds of voltaic batteries, some of which are used for telegraph work, others for electric bells, and others for blasting, so is it also with dynamos. One form is best for one purpose and another for another. One gives steadier currents, another is less liable to heat, a third is more compact, a fourth is cheaper, a fifth is less likely to reverse its currents, a sixth gives a greater volume of current, while a seventh evokes a higher electromotive force. Indeed, in the present transitional state of our knowledge with respect to dynamo-electric machinery, it is safe to assert that, for a long time to come, there will be no finality attained to. As with the steam-engine, however, so with the dynamo-machine, there will probably be a constant and progressive evolution, finally settling down upon two or three typical forms, which will survive the innumerable comparatively crude machines which have taken shape and come into active service.

Dynamo-Electric Machinery.

II.

THE DYNAMO IN PRACTICE.

IT was pointed out, at the conclusion of the former lecture, that neither of the four fundamental methods of exciting the field-magnetism of a dynamo was perfect in theory, since neither could enable a machine either to generate a constant current, or to maintain a constant electromotive force, whatever the resistance of the external circuit for the time being. Now, as the first function of a dynamo in practice is to feed with sufficiency and regularity a system of lamps, and as those lamps are always* in practice arranged either in series or in parallel, it is clear that in the former case a constant current, and in the latter a constant electromotive force is required.

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* I am aware that occasionally incandescent lamps have been arranged with two or three lamps, in series, in each parallel, or on a multiple series plan. I am not aware of any such arrangement having been satisfactory. [The multiple series system has been adopted by Edison, in his village lighting plant, recently erected at Roselle, N. J., in which three lamps are placed in each parallel. The arrangement is said to operate successfully.—F. L. P.]

COMBINATION METHODS.

The discovery of the method of rendering a dynamo machine automatically self-adjusting, so that either its electromotive force (according to circumstances) shall be constant, is due to M. Marcel Deprez, and is a result of the considerations arising from the study of the diagrams of the characteristic curves of dynamos.* M. Deprez has, in fact, shown mathematically that if a dynamo be wound with a double set of coils, one of which can be traversed by an independent current, whilst the other set is traversed by the current of the machine itself, there can always be found a certain critical velocity of driving, for which, provided the field-magnets are far removed from their saturation point, the desired condition is fulfilled. Other combination methods have been suggested by Professor Perry and others; and, as the whole matter promises to be of utmost importance in the future practice of constructing dynamos, a summary of the principal methods may be worth tabulating.

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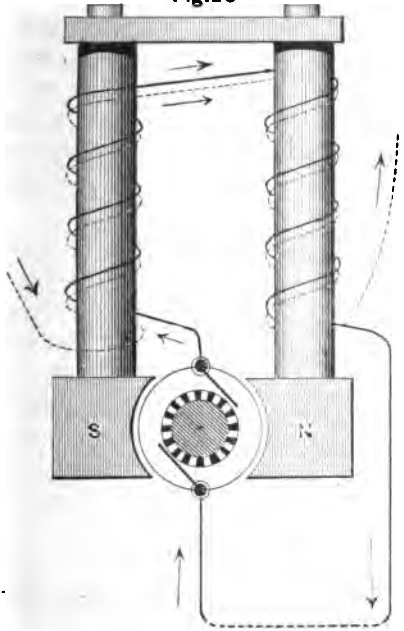
* See *La Lumiere Electrique*, December 3, 1881.

(1.) *Series and Separate* (*for Constant E. M. F.*), *Deprez.*—This method, illustrated in Fig. 20, can be applied to any ordinary dynamo, provided the coils are such that a separate current from an independent source can be passed through a part of them, so that there shall be an initial magnetic field, independent of the main circuit current of the dynamo. When the machine is running, the electromotive force producing the current will depend partly on this independent excitement, partly on the current's own excitement of the field magnets. If the machine be run at such a speed that the quotient of the part of the electromotive force due to the self-excitement, divided by the strength of the current, is numeri-

Fig.20



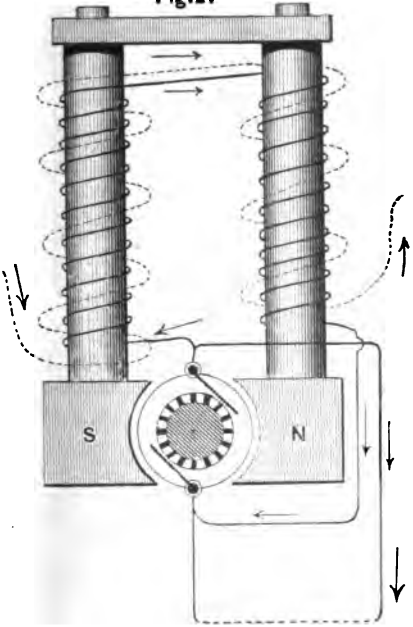
COMBINATION OF SERIES AND SEPARATE.

cally equal to the internal resistance of the machinery, then the electromotive force in the circuit will be constant, however the external resistances are varied. M. Deprez has further shown that this velocity can be deduced from experiment, and that, when the critical velocity has once been determined, the machine can be adjusted to work at any desired electromotive force, by varying the strength of the separately exciting current to the desired degree.

(2.) *Shunt and Separate* (*for Constant Current*), *Deprez.*—When cases arise, as for a set of arc lamps in series, in which it is desired to maintain the current in the circuit at one constant strength, the previous arrangement must be modified.as indicated in Fig. 21, by combining a shunt winding with coils for a separately exciting current. This arrangement is, in fact, that of a shunt-dynamo, with an initial magnetic field independent of the strength of the current in the circuit.

Seeing that the only object in providing the coils for separate excitement is to secure an initial and independent magnetic field, it is clear that other means may be employed to bring about a similar result.

Fig.21



SHUNT AND SEPARATE.

(3) *Series and Magneto* (*Constant E. M. F.*), *Perry.*—The initial electromotive force in the circuit, required by

Deprez's theory, need not necessarily consist in there being an initial magnetic field of independent origin. It is true that the addition of a permanent magnet to give an initial partial magnetization to the pole-pieces of the field magnets, would meet the case to a certain extent; but Professor Perry has adopted the more general solution of introducing into the circuit of a series-dynamo a separate magneto machine, also driven at a uniform speed, such that it produces in the circuit a constant electromotive force equal to that which it is desired should exist between the leading and return mains.*

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* Professor Perry gives, in his specification, the following numerical illustration, to which the only exception that can be taken is, that with so high a resistance as that of three ohms in the machine the system must be very uneconomical. "As an example, if there is only one dynamo machine, and if the resistance of the main cable, return cable and machines, in fact, of that part of the total circuit which is supposed to be constant, be, let us suppose, three ohms, then we find that the dynamo machine ought to be run at such a speed that the electromotive force, in volts, produced in its moving parts is three times the current in ampères, which flows through the field-magnets, consequently this

This arrangement, which is depicted in Fig. 22, may be varied by using a shunt-wound dynamo, the magnets being, as before, included in the part of the circuit

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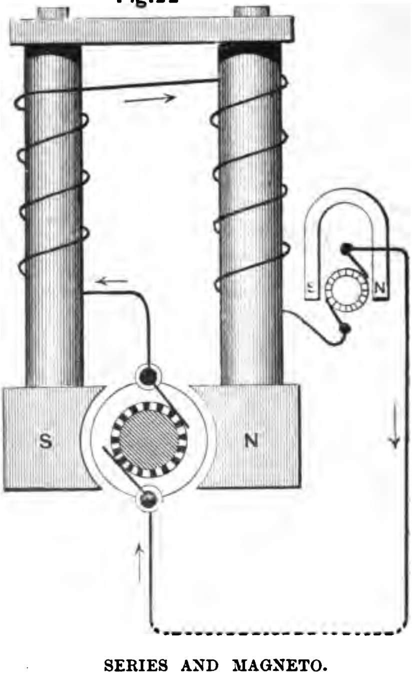
speed can readily be found by experiment. Suppose this constant electromotive force of the magneto machine to be 50 volts; its resistance 3 ohms, and the resistance of the dynamo machine and of the other unchanging parts of the circuit 2.7 ohms; and suppose that the speed is that at which the electromotive force produced by the rotating armature of the dynamo is three times the current. Now let there be a consumer's resistance of 2 ohms, the total resistance is 5 ohms. Evidently the electromotive force produced in the dynamo is 75 volts (for call this electromotive force x, then the current will be

$$x \div 3 \text{ whence it follows that } \frac{x+50}{5} = \frac{x}{3}$$

or $3x + 150 = 5x$, or $x = 75$) and the total electromotive force in the circuit is, therefore, 125 volts, and, as the total resistance is 5 ohms, the current is 25 ampères, giving an electromotive force of 50 volts between the ends of the consumers' part of the circuit. Now, if the consumers' resistance increases to, say 12 ohms, by some of the consumers ceasing to use their circuits, there is an instantaneous alteration of the electromotive force produced in the dynamo to 12½ volts, or 62½ volts in the whole circuit, and 62½ divided by 15 gives 4⅙ ampères; and this means 4⅙ multiplied by 12 or 50 volts as before, between the ends of the consumers' part of the circuit. Here, again, the calculation is:

$$\frac{x+50}{15} \quad \frac{x}{3} \text{ whence } 3x+150=15x, \text{ or } 12\tfrac{1}{2}=x. \quad \text{(S.P.T.)}$$

Fig.22



SERIES AND MAGNETO.

outside the machines. The combination of a permanent magnet with electro-magnets in one and the same machine, is much older than the suggestions of either Deprez or Perry, having been described by Hjörth in 1854.

(4.) *Shunt and Magneto* (*Constant Current*), *Perry.*—Perry's arrangement for constant current is given in diagram in Fig. 23, and consists in combining a shunt-dynamo with a magneto machine of independent electromotive force, this magneto machine being inserted either in armature part or in the magneto-shunt coils of the machine. As before, a certain critical speed must be found from experiment and calculation.

(5.) *Series and Shunt.*—A dynamo having its coils wound, as in Fig. 24, so that the field-magnets are excited partly by the main current, and partly by a current shunted across the brushes of the machine, is no novelty, having been used in Brush dynamos* for some years

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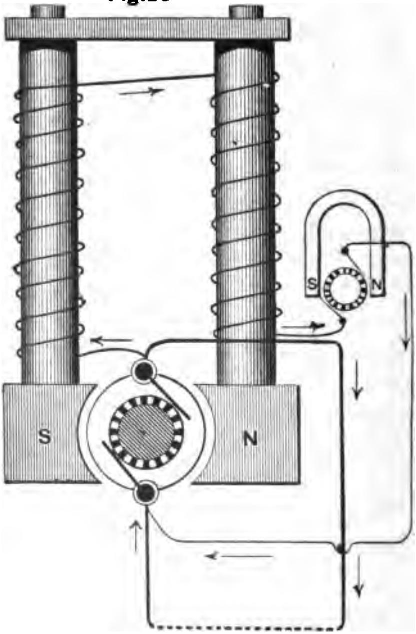
* The shunt part of the circuit, originally called the "teazer," was adopted at first in machines for electroplating, with the view of preventing a reversal of the current by an inversion of the magnetization of the field-magnets, but has been retained in some other patterns of machine on account of its usefulness in "steadying" the current. I am informed that Messrs. Siemens and Halske have also used this combination for some time past.

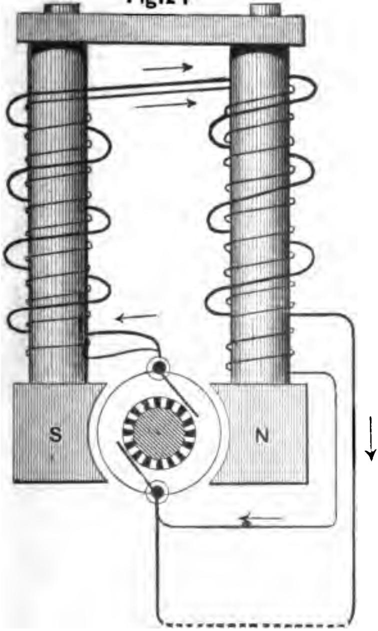
Fig.23



SHUNT AND MAGNETO.

past. The arrangement is not as perfect as either of the preceding, being more limited in operation. If the shunt coils

Fig. 24

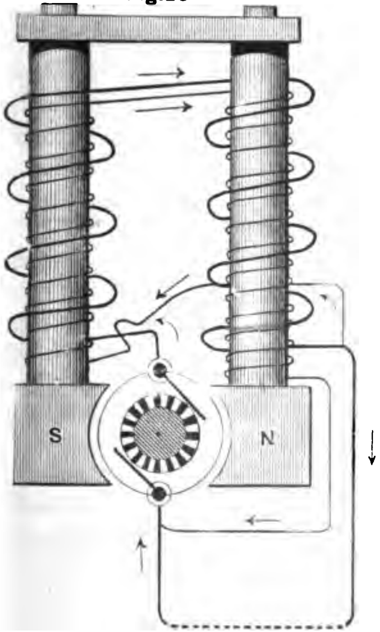


SERIES AND SHUNT.

be comparatively few, and of high resistance, so that their magnetizing power is small, the machine will give approximately a uniform electromotive force; whereas, if the shunt be relatively a powerful magnetizer, as compared with the few coils of the main circuit, the machine will be better adapted for giving a constant current; but, as before, each case will correspond to a certain critical speed, depending on the arrangements of the machine.

(6.) *Series and Long Shunt.*—I propose to give this name to a combination closely resembling the preceding, which has not yet, so far as I am aware, been actually tried. If, as in Fig. 25, the magnets are excited partly in series, but also partly by coils of finer wire, connected as a shunt *across the whole external circuit,* then the combination should be more applicable than the preceding to the case of a constant electromotive force, since any variation in the resistance of the external circuit will produce a greater effect in the "long shunt" than would be produced if the resistance of the field-magnets were included in the part of the main circuit external to the shunt.

Fig.25



SERIES AND LONG SHUNT.

Although the last two combinations are not such perfect solutions of the problem as those which precede, they are more likely, in my opinion, to find an immediate application,* since they can be put into practice upon any ordinary machine, and do not require, as in the first four combinations, the use of separate exciters, or of independent magneto-machines.

All these arrangements presuppose a constant velocity of driving; but they are not the only ones consistent with this condition. An ordinary series-dynamo may be made to yield a constant current, by introducing across the field-magnets a shunt of variable resistance, the resistance of the shunt being adjusted automatically by an electro-magnet, whose coils form part of the circuit. This is actually done in the automatic regulator attached to Brush dynamos, as used in supplying a series of arc lights. A shunt-dynamo may similarly be controlled, so as to yield a uniform electromotive force, by introducing a variable resistance into the shunt-magnet circuit, as is done in some of Edison's dynamos. To make the arrangement perfect, this variable resistance should be automatically adjusted by an electro-magnet whose coils are an independent shunt across the mains of the external circuit.

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* Since the above was written, an account of a similar combination to the 5th mentioned above has appeared in the pages of the *Electrician*, under the name of Crompton's Compound Dynamo. Mr. R. M. Rosanquet, of St. John's College, Oxford, has also suggested a similar arrangement for charging accumulators with a constant electromotive force.

Yet another way of accomplishing the regulation of dynamos is possible in practice, and this without the condition of a constant speed of driving. Let the ordinary centrifugal governor of the steam-engine be abandoned, and let the supply of steam be regulated, not by the condition of the velocity of driving, but by means of an electric governor, such as an electro-magnet working against an opposing spring. If this electro-magnetic governor is to maintain a constant electromotive force, its coils must be a shunt to the mains of the circuit. If it is to maintain a constant current, its coils must be part of the main circuit. Such a governor ought to be more reliable and rapid than any centrifugal governor intended to secure a uniform speed of driving.

ORGANS OF DYNAMOS.

I now propose to return to some of the rules and suggestions which we arrived at a week ago, in considering the dynamo in theory, and see how they are borne out in the dynamo as constructed in practice. I shall try to illustrate the various points that come under review, as far as possible, from the more recent types of dynamos.

FIELD-MAGNETS.

In the classification of dynamos laid down in my first lecture, we found that those of the first class required a single approximately uniform field of force, whilst those of the second class required a complex field of force differing in intensity and sign at different parts. Accordingly, we find a corresponding general demarcation between the field-magnets in the two classes of machine. In the first, we have usually two pole-pieces on opposite sides of a rotating armature. In the second, a couple of series of poles set alternately round a circumference or crown, the coils which rotate being set upon a frame between two such crowns of poles.

Confining ourselves, at first, to the first-class of machines, we find that, in practice, their magnets differ widely in construction and design. In very few of the existing patterns is there much trouble taken to secure steady magnets, by making them long, heavy and solid, or with very heavy pole-pieces. I have repeatedly, in testing dynamos, had to report that an unnecessary amount of wire had been wound upon the field-magnets; and I find that the usual reply is that with less wire the machine does not work so well. If, however, it is found necessary to wind so many coils upon the magnets as to bring them practically to saturation long before the machine is doing its maximum work, it is clear that either the iron is insufficient in quantity, or it is deficient in quality. In the Bürgin machines, where cast-iron field-magnets are employed, the smaller magnetic susceptibility of this metal is made up for by employing a great weight of it. In Siemens's smaller dynamos, the amount of iron employed in the field-magnets would be quite insufficient if it were not of high quality. As it is, I am of opinion, the mass of it (especially in the polar parts) might, with advantage, be increased. In some of the early machines of Wilde, and in Edison's well-known dynamos, long field-magnets, with heavy pole-pieces, are found. Edison's dynamos, indeed, are all remarkable in this feature; the pole-pieces and the yoke connecting the iron cores of the coils are made abnormally heavy. This is not more noticeable in the giant dynamos, used at the Holborn viaduct (see Fig. 30), than in the smaller machines used in isolated installations for sixty and for fifteen lights.

The principle of shaping the magnets

so that their external form approximates to that of the magnetic curves of the lines of force, is to some extent carried out in such widely differing types of machine as the Gramme with "Jamin" magnet, the Jürgensen dynamo, and Thomson's "mousemill" dynamo. The two machines last named exhibit several curious contrasts. In the Jürgensen, the field-magnets have heavy pole-pieces; in the Thomson there are none; and in the Thomson machine the iron core is thicker at the middle than at the ends. In both there are auxiliary internal electro magnets fixed within the rotating armature, to concentrate and augment the intensity of the field, according to the device patented by Lord Elphinstone and Mr. Vincent. In the Thomson machine the coils are heaped on more thickly at the middle of the field-magnets; in the Jürgensen, the coils are crowded up around the poles. The latter arrangement I condemned from the point of view of theory last week. If we may judge from a report on this machine by Professors Ayrton and Perry,* the arrangement is not satisfactory in practice, as there are more coils than suffice to magnetize the magnets. Is it possible that the mistake is not in having too many coils, but in having them in the wrong place?

Another suggestion, which was indicated from theoretical considerations, was that of laminating the pole-pieces, so as to prevent the production in them of wasteful Foucault currents. Here I find that but one machine has been designed in which this precaution is carried into effect. This is the disk-dynamo of Drs. Hopkinson and Muirhead, the field-magnets of which are made up of laminæ of iron, cast into a solid iron backing.†

Another matter in which, up to the present time at least, there is nothing but empirical practice to guide us, is the form to be given to pole-pieces, in order

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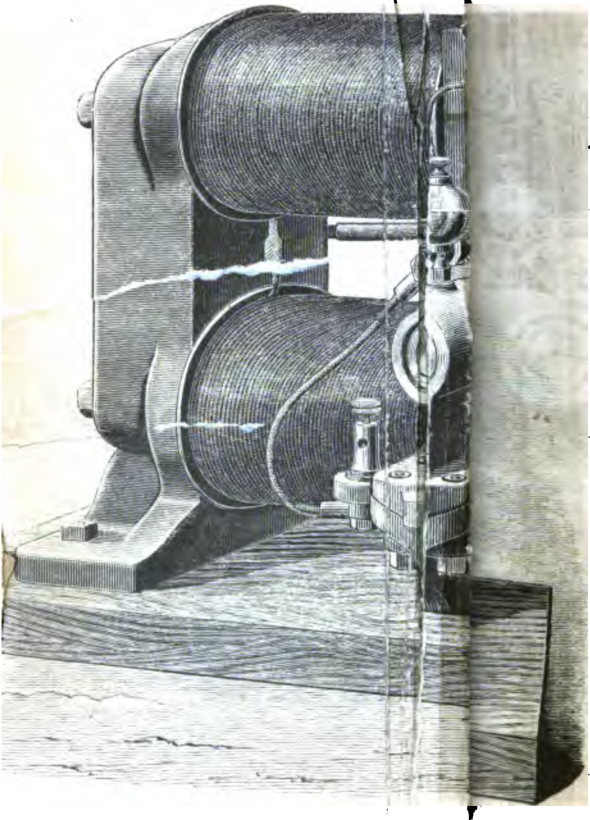
* See *Electrical Review*, Sept. 23, 1882.

[† This is also done in the Weston machines made by the U. S. Electric Lighting Co., at Newark, N. J. See Weston's patent, No. 211,811, Jan. 14, 1880.]



VON D

to produce the best effect. In fact, we have such singular divergence in practice, as to suggest the thought that little importance has been attached to the matter. Yet upon the form and extent given to the pole-pieces, depend considerations of no less importance than the reduction of idle wire in the armature, the reduction of sparking at the commutator, and the avoidance of counter-electromotive forces in the armature. If the pole-pieces are badly shaped for their work, or approach one another too far round the armature, they may completely perturb the approximate uniformity of the field, and may cause the central portion of the field to be of much weaker intensity than the two lateral regions between the edges of the pole-pieces. When this is the case, the rotating coils are virtually moving in a double field, and it is even possible that, in consequence, the direction of the currents induced in the individual coils may be reversed four or six times as they make one rotation. In such a case the distribution of potential round the separate bars of the commutator will be abnormal, as we shall see later on.

ARMATURES.

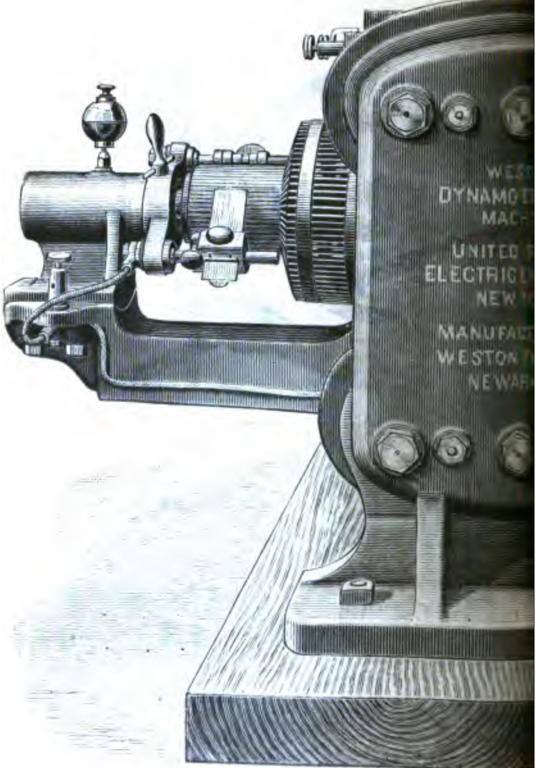
The armatures of dynamos of the first class may be roughly classified in three groups, according to the manner of arranging the coils. These three groups are—

(1.) *Ring armatures*, in which the coils are grouped upon a ring, whose principal axis of symmetry is its axis of rotation also.

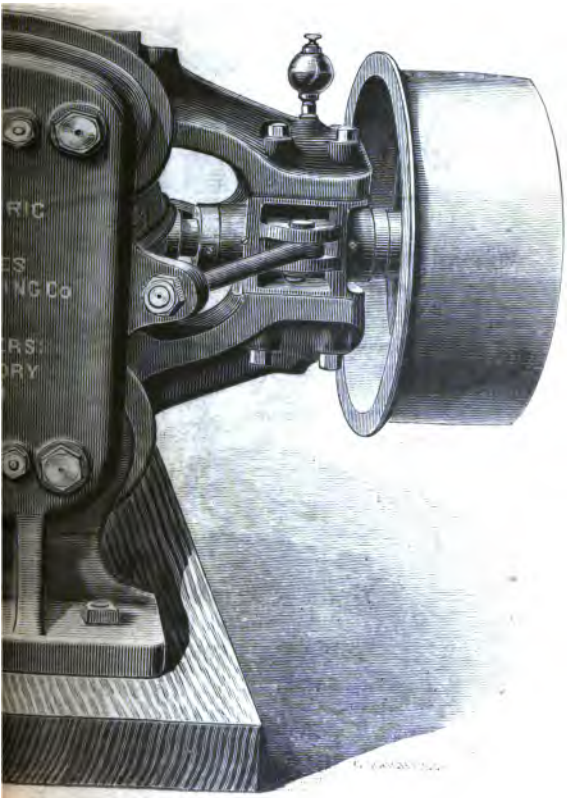
(2.) *Drum armatures*, in which the coils are wound longitudinally over the surface of a drum or cylinder.

(3.) *Pole armatures*, having coils wound on separate poles, projecting radially all round the periphery of a disc or central hub.

(To these we shall add a fourth form, namely, that of *Disk armatures*, when we deal with dynamos of the second class.)



Weston Dynamo Elec

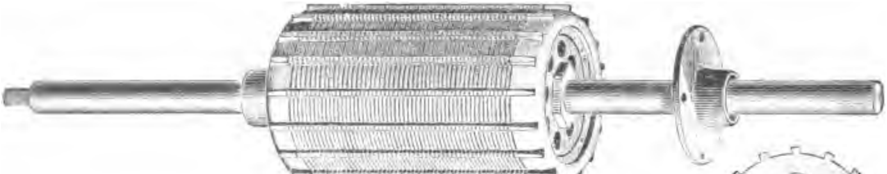


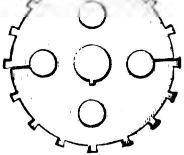
Machine.—End View.

The object of all these combinations is to obtain the practical continuity of current spoken of in section *t* of the first lecture. Some of the individual coils should be moving through the position of maximum action, whilst others are passing the neutral point, and are temporarily idle. Hence, a symmetrical arrangement around an axis is needed. Ring-armatures are adopted in practice in the dynamos of Pacinotti, Gramme, Schückert, Gülcher, Fein, Heinrichs, De Meritens, Brush, Jürgensen, and others. Drum armatures are found in the Siemens (Alteneck), Weston, Edison, Elphinstone-Vincent, Laing, and other machines, Pole-armatures are used in the dynamos of Allen and of Lontin. There are several intermediate forms. The Bürgin armature consists of eight or ten rings, side by side, so as to form a drum. The Lontin (continuous-current dynamo) has the radial poles affixed upon the surface of a cylinder. The Maxim armature is a hollow drum wound like a Gramme ring, and has, therefore, a great quantity of idle wire on the inner surface of the drum. The Weston armature has the drum surface cut up into longitudinal poles; there is a similar armature by Jablochkoff, in which the .poles are oblique.

Ring armatures are found in many machines, but the ingenuity of inventors has been exercised chiefly in three directions; the securing of practical continuity; the avoidance of Foucault currents in the cores, and the reduction of useless resistance. In the greater part of these machines, the coils that form the sections of the ring are connected in series, the end of one to the beginning of the next, so that there is a continuous circuit all round, an attachment being made between each pair to a bar or segment of the collector. Most inventors have been content to secure approximate continuity by making the number of sections numerous. One inventor, Professor Perry has built up a ring with coils wound obliquely, so that the one coil reaches the neutral point before the

WESTON SECTIONAL ARMATURE CORE.





SINGLE DISC OF
SECTIONAL ARMATURE.

preceding one has passed it. I cannot help doubting the advantage of this arrangement; which, moreover, presents mechanical difficulties in construction. Pacinotti's early dynamo had the coils wound between projecting teeth upon an iron ring. Gramme rejected these cogs, preferring that the coils should be wound round the entire surface of the endless core. To prevent wasteful currents in the cores, Gramme employed for that portion a coil of varnished iron wire of many turns. In Gülcher's latest dynamo, the ring-core is made up of thin flat rings cut out of sheet iron, furnished with projecting cogs, and laid upon one another.* The parts of the coils which pass through the interior of the ring (in spite of the late M. Antoine Breguet's ingenious proof that some of the lines of force of the field bent round and turned back into the core in this interior region) are com-

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[* This is an excellent construction, which appears to have been first devised by Edward Weston. See his patent, No. 209,532, Oct. 29, 1878.]

paratively idle. They cut very few lines of force as they rotate, and therefore offer a wasteful resistance. Inventors have essayed to reduce this source of loss, by either fitting projecting flanges to the pole-pieces (as in Fein's dynamo) or by using internal magnets (as in Jürgensen's dynamo), or else by flattening the ring into a disk form, so as to reduce the interior parts of the ring coils into an insignificant amount. This is done in the dynamos of Schückert and of Gülcher.* In Fig. 26 is given the latest form of Gülcher's dynamo. The field-magnets, front and back of the ring, are united on the right and left sides in a pair of hollow pole-pieces, which form cases over the ring, covering a considerable part of it. The collector is identical with that of Gramme, but very substantial.

The drum armatures may all be regarded as modifications of Siemens's well-known longitudinal shuttle-form armature of 1856, the multiplicity of sections

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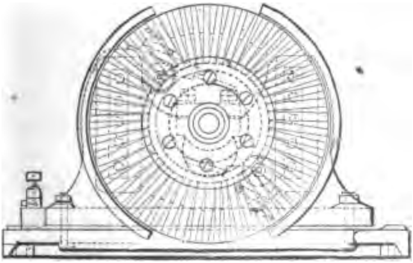
[* A similar organization is found in the Hochhausen dynamo.]

of the coils affording practical continuity in the currents. In some of Siemens's machines the cores are of wood, overspun with iron wire circumferentially, before receiving the longitudinal windings. In another of their machines there is a

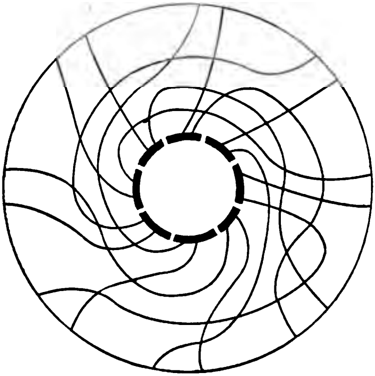
Fig. 26



GULCHER'S DYNAMO (NEW PATTERN).

stationary iron core, outside which the hollow drum revolves; in other machines again, there is no iron in the armature beyond the driving-spindle. In all of the Siemens armatures the individual coils occupy a diametral position with respect to the cylindrical core, but the mode of connecting up the separate diametral sections is not the same in all. In the older of the Alteneck-Siemens windings the sections were not connected together

Fig.27

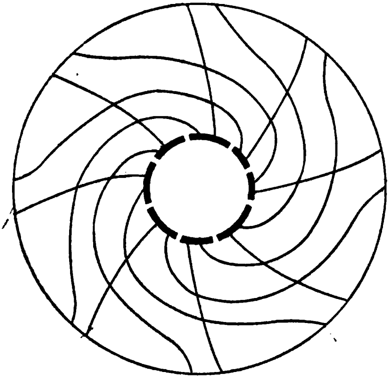


ALTENECK-SIEMENS WINDING (OLD).

symmetrically, the connections (for an eight-part collector) being as in Fig. 27. But in the more recent machines a symmetrical plan has been adhered to, as shown in Fig. 28.

In this system, as in the Gramme ring, the successive sections of coils ranged round the armature are connected together continuously, the end of one section and the beginning of the next being both united to one segment or bar of the collector. A symmetrical arrangement is, of course, preferable, not only for ease of construction, but because it is

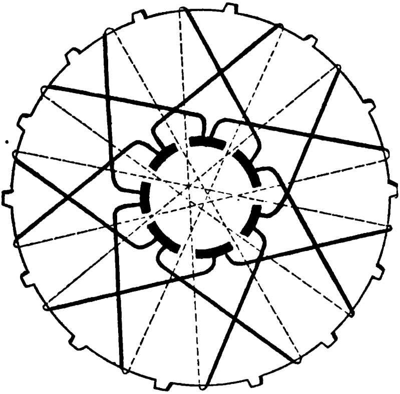
Fig. 28



ALTENECK-SIEMENS WINDING (NEW).

important that there should never be any great difference of potential between one segment of the collector and its next neighbor; otherwise there will be increased liability to spark, and to form arcs across the intervening gap. In Edison's modification of the drum-armature, the winding, though symmetrical in one sense, is singular, inasmuch as the number of sections is an odd number. In the first machines there were seven paths as shown in Fig. 29, taken from Edison's Patent Specification. In his latest giant machines, the number of sections is forty-nine. One consequence of this peculiarity of structure is that, if the brushes are set diametrically opposite to one another, they will not pass at the same instant from section to section of the collector; one of them will be short circuiting one of the sections, whilst the other is at the middle of the opposite collector. The armature of these latest of Edison's dynamos (Fig. 30, frontispiece) is not wound up with wire, but, like some of Siemens's electro-plating dynamos, is constructed of solid bars of copper, arranged round the periphery of a drum. The ends are connected across by washers or disks of copper, insulated from each

Fig.29



EDISON'S WINDING.

other, and having projecting lugs, to which the copper bars are attached. Such disks present much less resistance than mere strips would do The connections are in the following order: Each of the forty-nine bars of the collector is connected to one of the forty-nine disks at the anterior end of the drum, which is connected, by a lug-piece on one side, to one of the ninety-eight copper bars. The current generated in this bar runs to the further end of the machine, enters a disk at that end, crosses the disk, and returns along a bar diametrically opposite that along which it started. The anterior end of this bar is attached to a lug-piece of the next disk to that from which we began to trace the connections, it crosses this disk to the bar next but one to that first considered, and so round again. The two lug-pieces of the individual disks at the anterior end are, therefore, not exactly opposite each other diametrically, as the connections advance through $\frac{1}{49}$ of the circumference at each of the 49 paths. It will be noticed in Fig. 30 that the collector is very substantially built, and that a screen is fixed between the collector and the rest of the armature, to prevent any copper-dust from flying back or clogging the insulation between the bars or disks. There are no fewer than five pairs of brushes, the tendency to sparking being thereby greatly reduced. The figure does not show the structure of the armature itself, nor indicate the means taken to suppress Foucault currents. The core of the armature is made of very thin disks of iron,* separated, by mica or asbestos paper, from each other, and clamped together. Some exception may be taken to the use of such stout copper bars, as being more likely to heat from local currents than would be the case if bundles of straps, or laminæ of copper were substituted. And, indeed, the presence of the 4-horse power fan to cool the armature, is suggestive that continuous running is liable to heat the armature.

Before passing on from the subject of armatures, it is worth while to mention the peculiarity of form of the Bürgin armature, which has already been spoken of as consisting of eight, or in the newest Bürgin machines, as constructed by Mr. R. E. Crompton, of ten rings, set side by side.* Each ring is made of a hexagonal coil of iron wire, mounted upon light metal spokes, which meet the corners of the hexagon. Over this hexagonal frame six coils of covered copper wire are wound, being thickest at the six points intermediate between the spokes, thus making up the form of each ring to nearly a circle. Each of the six coils is separated from its neighbor, and each of the ten rings is fixed to the axis $\frac{1}{60}$ of the circumference in advance of its neighbor, so that the 60 separate coils are, in fact, arranged equidistantly (and symmetrically, as viewed from the end) around the axis. There is a 60 part collector, each bar of which is connected to the end of one coil and to the beginning of the coil that is one-sixtieth in advance; that is, to the corresponding coil of the next ring. This armature has the great practical advantages of being easy in construction, light, and with plenty of ventilation.

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* Disks of thin iron for a similar purpose are found in the dynamos of Jablochkoff, Weston, and Gülcher.

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* The *Bürgin* armature exhibited, was kindly lent by Messrs. R. E. Crompton & Co.

In the Elphinstone-Vincent dynamo there is a drum-armature of a somewhat distinct order, the separate coils being made of a rectangular form, and then laid upon the sides of a hollow papier-maché drum in an overlapping manner, and curved to fit it. The field is a complex one, with six external and six internal poles, and is very intense, owing to the proximity of these poles. The parallelogram-shaped coils are connected together so as to work as three machines, and feed three pairs of brushes; which may again be united, either in series or in parallel, or may be used to feed three separate circuits.

COLLECTORS.

In section *ab* of the first lecture, the main points to be observed in the construction of collectors are enumerated. Collectors of substantially such type as there described are common to all dynamos of the first class, except only the Brush dynamo, in which there is a multiple commutator, instead of a collector. The collector of Pacinotti's early machine differed only in having the separate bars alternately a little displaced longitudinally along the cylinder, but still so that the same brush could slip from bar to bar. Niaudet's modification, in which the bars are radially attached to a disk, is a mere variety in detail, and is not justified by successful adoption. In the collector, as used in Weston's dynamo, and in some forms of Schuckert's dynamo, the bars are oblique or curved, without, however, any other effect than that of prolonging the moment during which the brush, while slipping from contact with one bar to contact with the next, short-circuits one section of the coil.

In a well-arranged dynamo of the first class, the sections of the collector are traversed by currents which run from the negative brush in two directions round the successive coils, and meet at that bar of the collector which touches the positive brush. Each section of the coil thus traversed adds its own electromotive force to the current passing through it. Consequently, if one measures the difference of potential between the negative brush and the successive bars of the collector, one finds that the potential increases regularly all the way round the collecting cylinder, in both directions, becoming a maximum at the opposite side where the positive brush is. This can be verified by connecting one terminal of a voltmeter to the negative brush, and touching the rotating collector at different points of its circumference with a small metallic brush or spring attached by a wire to the other terminal of the voltmeter. If the indications thus obtained are plotted out round a circle corresponding to the circumference of the collector, the values give a curve like that shown in Fig. 31, which is plotted out from observations taken upon a Gramme dynamo.*

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* This diagram was plotted for me, and the measurements made at my request, by Mr. W. M. Mordey, who first drew my attention to some of the abnormal phenomena mentioned later.

It can be seen that, taking the negative brush as the lowest point of the circle, the potential rises perfectly regularly to a maximum at the positive brush. The same values are also plotted out as ordinates upon a horizontal line in Fig. 32. This form of diagram shows very clearly that the rise of potential is not equal between each pair of bars, otherwise the curve would consist merely of two oblique straight lines, sloping right and left from the central point. On the contrary, there is very little difference of potential between

Fig. 31

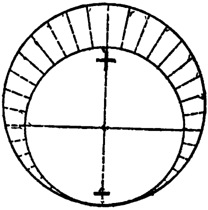
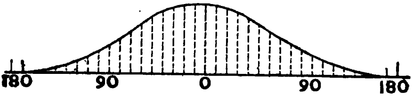


DIAGRAM OF POTENTIAL ROUND THE COLLECTOR OF GRAMME DYNAMO.

the collector bars close to the + brush on its right and left respectively. The greatest difference of potential occurs where the curve is steepest, at a position nearly 90° from the brushes, in fact, at that part of the circumference of the collector which is in connection with the coils that are passing through the position of best action. Were the field perfectly uniform, the number of lines of force that pass through a coil ought to be proportional to the sine of the angle which the plane of that coil makes with the resultant direction of the lines of force in the field, and the rate of cutting the lines of force should be proportional to

Fig.32



HORIZONTAL DIAGRAM OF POTENTIALS AT COLLECTOR OF GRAMME DYNAMO.

the cosine of this angle. Now the cosine is a maximum when this angle = 0°; hence, when the coil is parallel to the lines of force, or at 90° from the brushes, the increase of potential should be at its greatest—as very nearly realized in the diagram of Fig. 32, which, indeed, is very nearly a true "sinusoidal" curve. Such curves, plotted out from measurements of the distribution of potential at the collector, show not only where to place the brushes to get the best effect, but enable us to judge of the relative "idleness" or "activity" of coils in different parts of the field, and to gauge the actual intensity of different parts of the field while the machine is running. If the brushes are badly set, or if the pole-pieces are not judiciously shaped, the rise of potential will be irregular, and there will be maxima and minima of potential at other points. An actual diagram, taken from a dynamo in which these arrangements were faulty, is shown in Fig. 33, and again is plotted horizontally in Fig. 34; from which it will be seen, not only that the rise of potential was irregular, but that one part of the collector was more positive than the

Fig.33

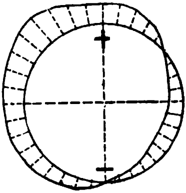
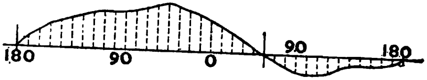


DIAGRAM OF POTENTIAL ROUND THE COLLECTOR OF A BADLY-ARRANGED DYNAMO.

Fig.34



HORIZONTAL DIAGRAM OF POTENTIALS AT COLLECTOR OF FAULTY DYNAMO.

positive brush, and another part more negative than the negative. The brushes, therefore, were not getting their proper difference of potential; and in part of the coils, the currents were actually being forced against an opposing electromotive force.

I believe that this method of plotting the distribution of potential round the collector will prove very useful in practice, and will explain various puzzling and anomalous results found by experimenters who have not known how to explain them. In a badly-arranged dynamo, such as that giving such a diagram as Fig. 33, a second pair of brushes, applied at the points showing maximum and minimum potential, could draw a good current without interfering greatly with the current flowing through the existing brushes! In fact, I find that this bad distribution, giving rise to anomalous maxima and minima, has actually been patented by a gentleman of the name of Kennedy,* who puts brushes on *six* different points of a collector!

Curves, similar to those given, can be obtained from the collectors of any dynamo of the first class—Gramme, Siemens, Edison, &c.—saving only from the Brush machine, which, having no such collector, gives diagrams of quite a different kind. It is, of course, not needful in taking such diagrams that the actual brushes of the machine should be in contact, or that there should be any circuit between them, though in such cases the field-magnets must be separately excited. It should also be remembered that the presence of brushes, drawing a current at any point of the collector, will alter the distribution of potential in the collector; and the manner and amount of such alteration will depend on the position of the brushes, and the resistance of the circuit between them.

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* British patent, No. 1,640 (1882).

The Brush Dynamo.

Before passing on to the dynamos of the second class, I have some remarks to make on that much mis-understood and mis-described machine, the Brush dynamo. Its armature—a ring in form, not entirely overwound with coils, but having projecting teeth between the coils like the Pacinotti ring—is unique. Though it thus resembles Pacinotti's ring, it differs more from the Pacinotti armature than that armature differs from those of Siemens, Gramme, Edison, Weston, Bürgin, &c.; for in all those successive sections are united in series all the way round, and constitute, in one sense, one continuous bobbin. But in the Brush armature there is no such continuity. The coils are connected in pairs, each to that diametrically opposite it, and carefully isolated from those adjacent to them. For each pair of coils there is a separate commutator, so that, for the ordinary ring of eight coils, there are four distinct commutators side by side upon the axis—one for each pair of coils. The brushes are arranged so as to touch at the same time the commutators of two pairs of coils, but never of two adjacent pairs; the adjacent commutators being always connected to two pairs of coils that lie at right angles to one another in the ring. The

arrangement is best studied graphically from the diagram given in Fig. 35.* In this figure, the eight coils are numbered as four pairs, and each pair has its own commutator, to which pass the outer ends of the wire of each coil, the inner ends of the two coils being united across to each other (not shown in the diagram). In the actual machine, each pair of coils, as it passes through the position of least action (*i. e.*, when its plane is at right angles to the direction of the lines of force in the field, and when the number of lines of force passing through it is a *maximum*, and the rate of change of these lines of force a *minimum*) is cut out of connection. This is accomplished by causing the two halves of the commutator to be separated from one another by about one-eighth of the circumference at each side. In the figure it will be seen that the coils marked 1_1 1_1 are "cut out." Neither of the two halves of the commutator touches the brushes. In this position, however, the coils 3_1 3_1, at right angles to 1_1 1_1, are in the position of best action, and the current powerfully induced in them flows out of the brush marked A, (which is, therefore, the negative brush) into that marked A′. This brush is connected across to the brush marked B, where the current re-enters the armature. Now, the coils 2, 2, have just left the position of best action, and the coils 4, 4, are beginning to approach that position. Through both these pairs of coils, therefore, there will be a partial induction going on. Accordingly, it is arranged that the current, on passing into B, splits, part going through coils 2, 2, and part through 4, 4, and re-uniting at the brush B′, whence the current flows round the coils of the field-magnets to excite them, and then round the external circuit, and back to the brush A. (In some machines it is arranged that the current shall go round the field-magnets after leaving brush A′, and before entering brush B; in which case the action of the machine is sometimes, though not correctly, described as causing its coils, as they rotate, to feed the field-magnets and the external circuit alternately). The rotation of the armature will then bring coil 2, 2, into the position of least action, when they will be cut out and the same action is renewed with only a slight change in the order of operation. The following table summarizes the successive order of connections during a half revolution:

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* This diagram I have constructed somewhat on the lines of a working model kindly lent me by Mr. Percy Allen, of the Anglo-American Corporation; which, however, was designed to show the action of larger dynamo, having twelve coils on the ring and six commutators.

First position. (Coils 1 cut out.)

$\mathrm{A}-3-\mathrm{A};\ \mathrm{B} < \substack{4\\2} > \mathrm{B};$

Field-magnets—External circuit—A.

Second position. (Coils 2 cut out.)

$\mathrm{A} < \substack{3\\1} > \mathrm{A};\ \mathrm{B}-4-\mathrm{B};$

Field-magnets—External circuit—A.

Third position. (Coils 3 cut out.)

$\mathrm{A}-1-\mathrm{A}$; $\mathrm{B} < \substack{2 \\ 4} > \mathrm{B}$;

Field-magnets—External circuit—A.

Fourth position. (Coils 4 cut out.)

$\mathrm{A} < \substack{3 \\ 1} > \mathrm{A}$; $\mathrm{B}-2-\mathrm{B}$;

Field-magnets—External circuit—A.

From this it will be seen that whichever pair of coils is in the position of best action, is delivering its current direct into the circuit; whilst the two pairs of coils which occupy the secondary positions are always joined in parallel the same pair of brushes touching the respective commutators of both.

One consequence of the peculiar arrangement thus adopted is, that measuring the potentials round one of the commutators with a voltmeter gives a wholly different result from that obtained with other machines. For one-eighth of the circumference on either side of the positive brush, there is no sensible difference of potential. There then comes a region in which the potential appears to fall off; but the falling off is here partly due to the shorter time during which the adjustable brush connected with the voltmeter and the fixed positive brush are both in contact with the same part of the

Fig. 36

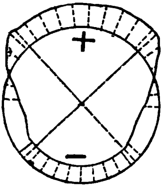

DIAGRAM OF POTENTIALS AT COMMUTATOR OF BRUSH DYNAMO.

commutator. Further on there is a region in which the voltmeter gives no indications corresponding to the cut out position; and again, on each side of the negative brush, there is a region where the polarity is the same as that of the negative brush. Fig. 36 is a diagram of a 6-light Brush taken at one commutator, the main +

brush being, however, allowed to rest (as in its usual position), in contact with both this commutator and the adjacent one.

From the foregoing considerations, it will be clear that the four pairs of coils of the Brush machine really constitute four separate machines, each delivering alternate currents to a commutator, which commutes them to intermittent unidirectional currents in the brushes ; and that these independent machines are ingeniously united in pairs by the device of letting one pair of brushes press against the commutators of two pairs of coils. Further, that these paired machines are then connected in series, by bringing a connection round from brush A′ to brush B.

The following experiment illustrates the independence of the four pairs of coils in the Brush dynamo.* The usual commutators of a small Brush dynamo were removed and replaced by eight brass collars, to each of which was united one end of one of the four pairs of coils. Against these rings pressed eight separate brushes, and the circuit of each of the four pairs of coils was completed, as shown in Fig. 37, through an ordinary detector galvanometer. On rotating the armature by hand, at a moderate speed, the needles of all four detectors are set vibrating to and fro by the alternate currents, not synchronously, but one after the other. If any of the four circuits are broken, the others go on as before.

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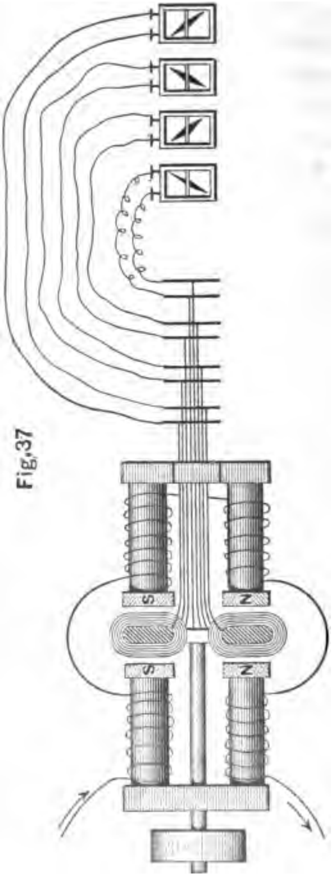
* This beautiful experiment was first shown me by Mr. P. Allen, who kindly fitted up the little Brush dynamo with the eight collars for this occasion.

DYNAMOS OF THE SECOND CLASS.

I now pass on to dynamos of the second class, in which coils are carried round to different parts of a magnetic field, whose intensity differs in different regions, or one, in different parts of which the lines of force run in opposite directions. Fig. 13 of my first lecture illustrated this principle; and we shall now consider how it is carried out in practice. In the early

Fig. 37



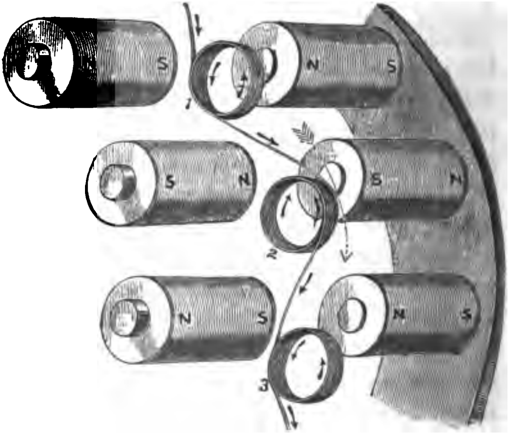
BRUSH DYNAMO ARRANGED WITH 4 DETECTOR GALVANOMETERS SHOWING ALTERNATE CURRENT INDUCED IN INDEPENDENT PAIRS BY COILS.

machine of Pixii a single pair of coils was mounted so as to pass in this fashion through parts of the field where the magnetic induction was oppositely directed. Such a machine, therefore, gives alternate currents, unless a commutator be affixed to the rotating axis. Niaudet's dynamo, which may be regarded as a compound Pixii mcahine, having the separate armature coils united like those of Gramme and Siemens in one continuous circuit, is furnished with the radial collector mentioned above. In the Wallace-Farmer dynamo is very nearly realized the condition of field of Fig. 13, there being a pair of poles at the top arranged so that the north faces the south pole, and another pair at the bottom where the south faces the north pole. The coils are carried round, their axis being always parallel to the axis of rotation, upon a disk; there being two sets of coils on opposite faces of two disks of iron set back to back. They are united precisely as in Niaudet's dynamo, and each disk has its own collector. Each bar of the collector is, moreover, connected, as in the dynamos of Pacinotti, Gramme, Siemens, &c., with the end of one coil, and the beginning of the next. In fact, the Wallace-Farmer machine is merely a double Niaudet dynamo with the cylindrical collectors. There is a serious objection to the employment of solid iron disks such as these. In a very short time they grow hot from the eddying Foucault currents engendered in them as they rotate. This waste reduces the efficiency of the dynamo. In the dynamo of Hopkinson and Muirhead, the disk armature takes a more reasonable shape. Instead of a solid disk of iron to support the coils, there is a disk built up of a thin iron strip wound spirally round a wooden center. The coils, of approximately quadrangular shape, and flat form, are wound upon the sides of this compound disk. The dynamo of Ball (the so-called "Arago-disk" machine) is similar in many respects, but has no iron cores to the armature coils.

ALTERNATE-CURRENT DYNAMOS.

But by far the most important of the dynamos of this second class are those usually known as *alternate-current machines.* This type of dynamo was originally created by Wilde, in 1867. The field-magnets, consist of two crowns of fixed coils, with iron cores, arranged so that their free poles are opposite to one another, with a space between them sufficently wide to admit the armature. The poles taken in order round each crown are alternately of north and south polarity, and opposite a north pole of one crown faces a south pole of the other crown. This description will apply to the magnets of the alternate current machines of Wilde and Siemens, to the so-called Ferranti machine, and, with certain reservations, to the machines of Lachausée and of Gordon. The armatures in almost all machines of this type consists of a *disk*, bearing at its periphery a number of coils, whose axes are parallel to the axis of rotation. The principle will be best understood by reference to Fig. 38, which gives a general view of the arrangement. Since the lines

Fig. 38.



PRINCIPLE OF ALTERNATE-CURRENT DYNAMOS.

of force run in opposite directions between the fixed coils, which are alternately S—N, N—S, as described above, the moving coils will necessarily be traversed by alternating currents; and as the alternate coils of the armature will be traversed by currents in opposite senses, it is needful to connect them up, as shown in the figure, so that they shall not oppose one another's action.

In Wilde's dynamo, the armature coils have iron cores, and the machine is provided with a commutator on the same principle as that used by Jacobi in his famous motor of 1838, consisting of two metal cylinders, cut like crown wheels, having the teeth of one projecting between those of the other, so that the brushes make contact against them alternately as they rotate. The brushes are, of course, fixed, so that they do not both touch the same part. This commutator Wilde usually applied to a few, or only one, of the rotating coils, and utilized the current thus obtained to magnetize the field-magnets. The main current was not so commuted, but was led away from a simple collector, consisting of two rings connected to the two ends of the armature circuit, each being pressed by one brush.

Siemens prefers to use a separate direct current machine to excite the field-magnets of alternate-current dynamo. In the armature of the latter the coils are wound usually without iron, upon wooden cores. In some forms of the machine, the individual coils are enclosed between perforated disks of thin German-silver. When currents of great strength are required, but not of great electromotive force, the coils are coupled up in parallel arc, instead of being united in series.

In a dynamo by Lachausée, which very strikingly resembles the preceding one, there is iron in the cores of the rotating coils. But the main difference is that the rotating coils are the field magnets, excited by a separate Gramme dynamo, whilst the coils, which are fixed in two crowns on either side, act as armature coils in which currents are induced.

Gordon's dynamo, the largest yet constructed, is constructed on the same lines as the Lachaussée machine ; but with many important improvements. In the first place, there are twice as many coils in the fixed armatures as in the rotating magnets, there being 32 on each side of the rotating disk, or, in all, 64 moving coils ; while there are 64 on each of the fixed circles, or 128 stationary coils in all. The latter are of an elongated shape, wound upon a bit of iron boiler-plate, bent up to an acute V form, with checks of perforated German silver as flanges. The object of thus arranging the coils, so that the moving ones shall have twice the angular breadth of the fixed ones, is to prevent adjacent coils of the fixed series from acting detrimentally, by induction, upon one another. The alternate coils of the fixed series are united together in parallel arcs, so that there are two distinct circuits, in either or both of which lamps can be placed ; or they can be coupled up together. Great care appears to have been taken, in the construction of this large machine, to guard against the appearance of

Foucault currents, by arranging the cores, frames, and coils, so that all metal parts of any size shall be slit, or otherwise structurally divided at right-angles to the direction of the induced electromotive forces.

Yet another alternate-current dynamo, identical in many respects with the Siemens alternate-current dynamo, has lately been brought out, under the name of the Ferranti machine. As in the machines of Wilde and Siemens, the electromagnets form two crowns with opposing poles. The point of difference is the armature, which, like that of Siemens, has no iron cores in his coils; but which, unlike that of Siemens, is not made up of coils wound round cores, but consists of zigzags of strip copper folded upon one another. There are eight loops in the zigzag (as shown in Fig. 39,) which depicts half only of the arrangement, and on each side are sixteen magnet poles; so that, as in Gordon's dynamo, the moving parts are twice the angular breadth of the fixed parts.

The advantage of the armature of zigzag copper lies in its simplicity of construction. Sir W. Thomson, who is the real inventor of this armature, proposed originally that the copper strips should be wound between projecting teeth on a wooden wheel, as indicated Fig. 40, in which is taken from the drawings of his British patent of December, 1881. He also proposed to use as field-magnets a form of electro-magnet of the kind known as Roberts, and also used by Joule, in which the wires that bring the exciting

Fig. 39.

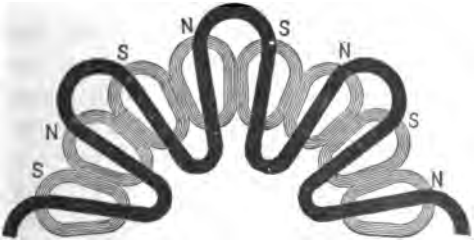
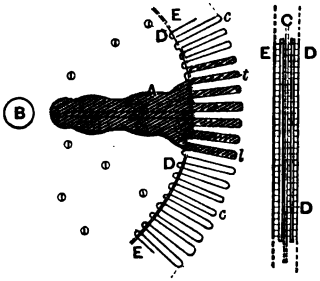


DIAGRAM OF FERRANTI'S ALTERNATE-CURRENT DYNAMOS.

current are passed up and down, in a zigzag form between iron blocks projecting from an iron frame. Fig. 41 shows the form, as indicated in the specification, the conducting strips being wound round

Fig. 40.



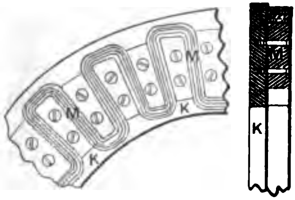
SIR W. THOMSON'S ZIGZAG WINDING OF ARMATURE FOR ALTERNATE-CURRENT DYNAMO.

between wrought-iron projections screwed to a cast-iron frame. I am not aware that this particular suggestion has been adopted as yet in practice.

Much more might be said concerning the two machines last described—the

Gordon and the Thomson dynamos—but time does not permit me to dwell longer upon them. And, indeed, I am not at all convinced that this type of machine, though at present it appears to be the fashionable one, is destined to prove of such very great value, simply because I doubt whether any dynamo that yields alternate currents can compete with continuous-current machines. For the purposes of a general system of distribution, where more than one dynamo must be available, and also for the purpose of supplying motors, alternate-current ma-

Fig. 41.



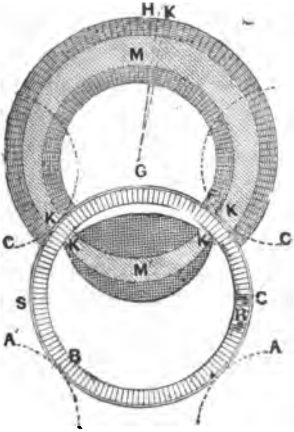
SIR W. THOMSON'S PROPOSED FIELD MAGNETS.

chines are quite out of the question. I will not therefore dwell longer upon them, than merely to remark that, besides the disk armatures now described, pole armatures have been employed in alternate-current machines by Gramme, Jablochkoff, and Lontin. Von Hefner Alteneck has gone a stage further, and, by the device of employing a disk armature in which the number of coils differed by two, or some other even number, from those of the field, and by the employment of a multiple-bar collected with complicated cross connections, has succeeded in converting this type of dynamo into a continuous-current machine.

THOMSON'S "MOUSE-MILL" DYNAMO.

One other dynamo, not belonging to the type I have been dealing with, is worthy of mention. This is Sir W. Thomson's "mouse-mill" dynamo, shown in Fig. 42, in diagram. I have noticed, *en passant*, several points in this machine—the form of its field-magnets and their coils, the internal electro-magnets, etc. The armature is a hollow cylinder, S S, made up of parallel copper bars, arranged like the bars of a mouse-mill (whence the name of the machine). These bars are insulated from each other, but are connected all together at one end. At

Fig. 42.



SIR W. THOMSON'S "MOUSE-MILL" DYNAMO.

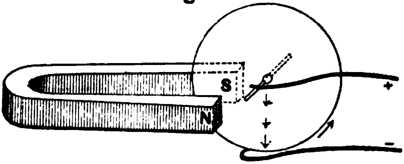
the other they serve as collector-bars, and deliver up the currents generated in them to the "brushes," which here are rotating disks of springy copper shown as dotted circles at C C in the figure. As the armature is a hollow barrel, with fixed electro-magnets within, it cannot be rotated on a spindle, but runs on friction rollers, A A′, by one or more of which it is driven.

Dynamos of the Third Class.

I now come to the third class of dynamos—those in which rotation of a conductor effects a continuous increase in the number of lines of force cut, by the device of arranging one part of the conductor to slide on or round the magnet.

The earliest machine which has any right to be called a dynamo, was in fact, of this class. Barlow and Sturgeon had shown that a copper disk, placed between the poles of a magnet (Fig. 43) rotates in the magnetic field when traversed by an electric current from its axis to its periphery, where there is a sliding contact. Faraday, in 1831, showed that by rotating a similar disk mechanically between the poles of a magnet continuous currents were obtained. These he drew off by collecting springs of copper or lead, one of which touched the axis (see Fig. 44), whilst the other pressed against the amalgamated periphery. He was thus "able to construct a new electrical machine."*

Fig. 43.



BARLOW'S WHEEL.

"Here, therefore, was demonstrated the production of a permanent (*i. e.* continuous) current of electricity by ordinary magnets." But Faraday did not stop short with ordinary magnets; he went on to employ the principle of separate excitement of his field-magnets. "These effects were also obtained from *electro-magnetic poles*, resulting from the use of copper helices or spirals, either alone or with iron cores. The directions of the motions were precisely the same; but the action was much greater when the iron cores were used, than without."[*] The invention of the dynamo dates, therefore, from 1831, and Faraday was its inventor, though he left to others to reap the fruits of his splendid discovery.[†]

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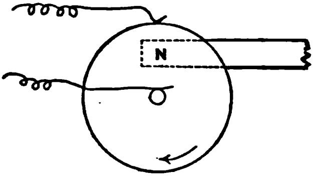
* *Experimental Researches*, § 83.

Fig. 44.



FARADAY'S DISK DYNAMO.

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[*] *Experimental Researches*, § 111.

[†] *Experimental Researches*, § 158: — "I have rather, however, been desirous of discovering new facts and new relations dependent on magneto-elec-

Such a machine, however, is impracticable, for several reasons; the peripheral friction is inadmissible on any but a small scale; moreover, the disposition of the field-magnets necessarily evokes wasteful eddy-currents in the disk, which, even if slit radially, would not be an appropriate form of armature for such a limited magnetic field.

Another method of obtaining a continuous cutting of the lines of force, is indicated in Fig. 45, where a sliding conductor travels round the pole of a magnet. Faraday even generated continuous currents by rotating a magnet with a sliding connection at its center, from which a conductor ran round outside, and made contact with the end-pivots which supported the magnet.

A similar arrangement was devised by Mr. S. Alfred Varley, about the year

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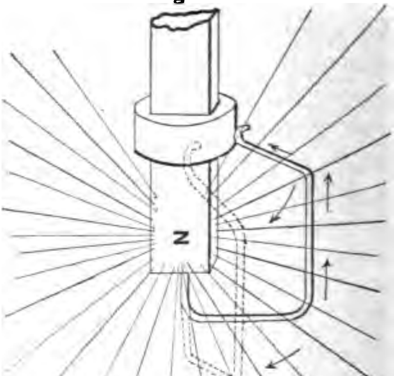
tric induction, than of exalting the force of those already obtained; being assured that the latter would find their full development hereafter." Can any passage be found in the whole range of science more profoundly prophetic, or more characteristically philosophic, than these words, with which Faraday closed this section of his researches?

1862. He rotated an iron magnet in a vertical frame, having a mercurial connection at the center. The current which flowed from both ends of the magnet toward the center was, in this machine—which, by the kindness of Mr. Varley, I am able to exhibit to you to-night—made to return to the machine, and to

Fig. 45.



ROTATION OF CONDUCTOR ABOUT POLE OF MAGNET.

pass through coils surrounding the poles of the rotating magnet; thus anticipating the self-exciting principle of later date. Mr. Varley also proposed to use an external electro-magnet to increase the action.

Quite recently, the same fundamental idea has been worked upon by Messrs. Siemens and Halske, who have produced a so-called "unipolar" machine.* In this remarkable dynamo there are two cylinders of copper, both slit longitudinally to obviate eddy-currents, each of which rotates round one pole of a U-shaped electro-magnet. A second electro-magnet, placed between the rotating cylinders, has protruding pole-pieces of arching form, which embrace the cylinders above and below. Each cylinder, therefore, rotates between an internal and an external pole of opposite polarity, and consequently cuts the lines of force continuously by sliding upon the internal pole. The currents from this machine are of very great strength, but of only a few volts of electromotive force. To keep down the resistance, many collecting brushes press on each end of each cylinder. This dynamo is actually at work for electro-plating.

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* This sounds like a *locus a non lucendo*, for the machine has two poles. But the name is derived from the term "unipolar induction," which Continental electricians give to the induction of currents by the process of "continuous cutting," which we are now dealing with. I do not adopt the term, as it is needlessly mystifying.

The only other dynamo of this class, of which I have seen any published notice, is one recently patented by Mr. E. L. Voice, in which a coil armature wound upon an iron ring, is so placed that the iron ring is itself one pole of a magnet, a projecting pole-piece from the other pole being fixed near it, so that the coils fixed upon one pole glide round and cut the lines of force proceeding from the other pole. Whether this machine will be a practical one remains to be seen.

We are, however, far from having arrived at finality in the design and construction of dynamo-electric machines. All we can yet say is, that we appear to be approaching the time when practice will no longer be a species of blundering along into success or failure. For every-day theory is more brought to bear in practice, and will soon enable us to predict with certainty beforehand what will be the merit of a dynamo of any particular design; and even to say not only what its cost will be, and what its efficiency and maximum duty, but also how many volts of electromotive force, and how many ampères of current it will put at our disposal. In short, the application of theory in the manufacture of dynamos must rapidly lead to great and substantial improvements in the dynamo in practice.

Dynamo-Electric Machinery.

III.

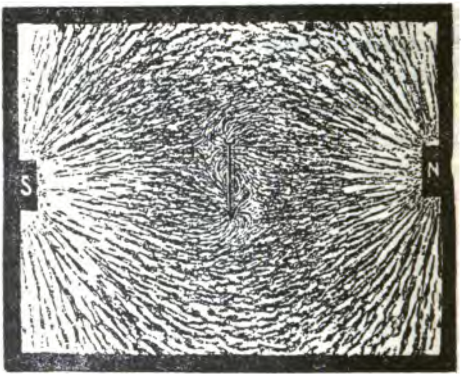
THE DYNAMO AS A MOTOR.

In my first lecture, I laid down the definition that dynamo-electric machinery meant "machinery for converting the energy of mechanical motion into the energy of electric currents, or *vice versa.*" In the two lectures which I have already had the honor of delivering, I have treated the dynamo solely in its functions as a generator of electric currents. In this third lecture I come to the converse function of the dynamo, namely, that of converting the energy of electric currents into the energy of mechanical motion.

An electric-motor, or, as it was formerly called, an electro-magnetic engine, is one which does mechanical work at the expense of electric energy; and this is true, no matter whether the magnets which form the fixed part of the machine be permanent magnets of steel or electromagnets. Any one, in fact, of the four kinds of dynamo, can be used conversely as a motor, though, as we shall see, some more appropriately than others. But whether their field magnets be of permanently magnetized steel or of temporarily magnetized iron, all these motors are electro-magnetic in principle; that is to say, there is some part either fixed or moving which is an electro-magnet, and which as such attracts and is attracted magnetically.

Every one knows that a magnet will attract the opposite pole of another magnet, and will pull it round. We know, also, that every magnet placed in a magnetic field tends to turn round and set itself along the lines of force. Let me, as a first illustration of this class of actions, exhibit to you the nature of the forces at work in the magnetic field. In the figure which I now throw upon the screen (Fig. 46), we have, in the first place, a simple magnetic field produced between the poles of two strong magnets, one on the right, the other on the left. Between the two, confined forcibly at right-angles to the lines of force, I hold a small magnetic needle. Iron filings sprinkled in the field reveal the actions at work in a most instructive way. Faraday, who first taught us the significance of these mysterious lines of force, has told us that we may reason about them as if they tended to

Fig. 46.



ACTION OF MAGNETIC FIELD ON A MAGNETIC NEEDLE.

contract or grow shorter. Now a simple inspection of Fig. 46 will show that the shortening of the lines of force must have the effect of rotating the magnetic needle upon its center, through an angle of 90°, for the lines stream away on the right hand above, and on the left hand below, in a most suggestive fashion. It is not, therefore, difficult to understand that very soon after the invention of the electro-magnet, which gave us for the first time a magnet whose power was under control, a number of ingenious persons perceived that it would be possible to construct an electro-magnetic engine in which an electro-magnet, placed in a magnetic field, should be pulled round; and further, that the rotation should be kept up continuously, by reversing the current at an appropriate moment.* As a matter

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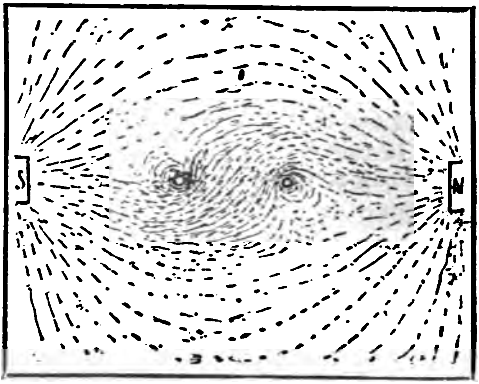
[*Thomas Davenport, an ingenious blacksmith of Brandon, Vermont, constructed what was probably the earliest practical electric motor, with which he is said to have operated a printing press. He employed two or more movable and two or more stationary magnets, the former projecting radially from a shaft, and the latter either permanent or electro-magnets. See his patents, United States, No. 132, Feb. 25, 1837; and Great Britain, No. 7386 of 1837.—F. L. P.]

of fact, a mere coil of wire, carrying a current, is acted upon when placed in the magnetic field, and is pulled round as a magnet is. Fig. 47 shows how, in this

Fig. 47.



ACTION OF MAGNETIC FIELD ON A WIRE CARRYING A CURRENT.

case, the lines of force reveal the action. The magnetic field is as before, produced between the ends of two large magnets. The two round spots are two holes drilled in the sheet of glass, where the wire which carried the current came up through the glass and descended again. You will notice how the lines of iron filings, which would, if there were no current, run simply across from left to right, are bent out of their course. If these lines could shorten themselves, they must, of necessity, twist the loop of wire round, and cause it to set at right angles to its present position.

On this very principle was constructed the earliest electric-motor of Ritchie,* so well known in many forms as a stock piece of electric apparatus, but little better in reality than a toy.

A great step in advance was made by Jacobi, who, in 1838, constructed the multipolar machine, of which we give a representation in Fig. 48.† This motor,

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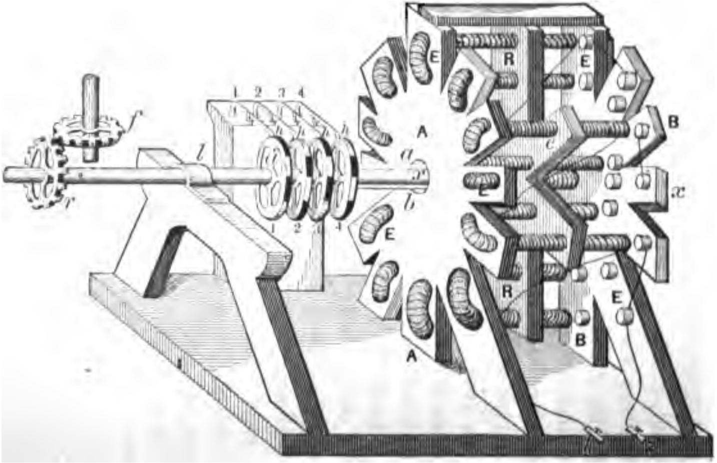
[* *Davis's Manual of Magnetism*, Ed. of 1857, p. 213.—H. R. B.]

[† A motor upon the same principle as that of Jacobi, and very similar to it in mechanical construction, was patented in the United States by Solomon Stimpson, of New York, Sept. 12, 1838, No. 910. Davenport, in 1837, employed substantially the same organization. See note, p. 155.—F. L. P.]

Fig.48



JACOBI'S ELECTRIC MOTOR (1838.)

which Jacobi designed for his electric boat, had two strong wooden frames, A and B, in each of which a dozen electromagnets were fixed, their poles being set alternately. Between them, upon a wooden disk, were placed another set of electro-magnets, which, by the alternate attraction and repulsion of the fixed poles, were kept in rotation, the current which traversed the rotating magnets being regularly reversed at the moment of passing the poles of the fixed magnets by means of a commutator, consisting, according to Jacobi's directions, of four brass-toothed wheels, having pieces of ivory or wood let in between the teeth for insulation. Jacobi's motor is, in fact, a very advanced type of dynamo, and differs very little in point of design from one of Wilde's most successful forms.*

A still earlier rotating apparatus, and, like Ritchie's motor, a mere toy, was Barlow's wheel, Fig. 43, described in 1823.

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* Wilde's is, however, designed as a generator. Jacobi's, on the contrary, was designed as a motor; though, of course, it would generate currents if driven round by mechanical power.

This instrument, interesting as being the forerunner of Faraday's disk dynamo, is the representative of an important class of machines, namely, those which have a sliding contact merely, and need no commutator.

A fourth class of motors may be named, wherein the moving part, instead of rotating upon an axis, is caused to oscillate backwards and forwards. Professor Henry, to whom we owe so much in the early history of electro-magnetism, constructed, in 1831, a motor with an oscillating beam, alternately drawn backwards and forwards by the intermittent action of an electro magnet.* Dal Negro's motor of 1833 was of this class; in it a steel rod was caused to oscillate between the poles of an electro-magnet, and caused a crank, to which it was geared, to rotate in consequence. A distinct improvement in this type of machine was introduced by Page, who employed hollow coils or

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[**Am. Jour. Sci.*, vol. xx., p. 340, *et seq.* This was the first electro-motor proper ever constructed, and was designed merely to demonstrate the possibility of such an application of electricity.—F. L. P.]

bobbins as electro-magnets, which, by their alternate action, sucked down iron cores into the coils, and caused them to oscillate to and fro.* Motors of this kind form an admirable illustration of one of the laws of electro-magnetics, first formulated by Gauss, but developed later by Maxwell, to the effect that a circuit acts on a magnetic pole in such a way as to make the number of magnetic lines of force that pass through the circuit a maximum. Once more I have recourse to iron filings to illustrate this abstract proposition of electric geometry.

In the figure before you (Fig. 49), the north pole of a bar magnet is placed opposite a circuit or loop of wire traversed by a current, and which comes up through the glass at the lower hole, and descends at the upper hole. The tendency to draw as many as possible of the magnet's lines of force into the embrace of the circuit is unmistakable. If now we reverse the current, what do we find? Fig. 50 sup-

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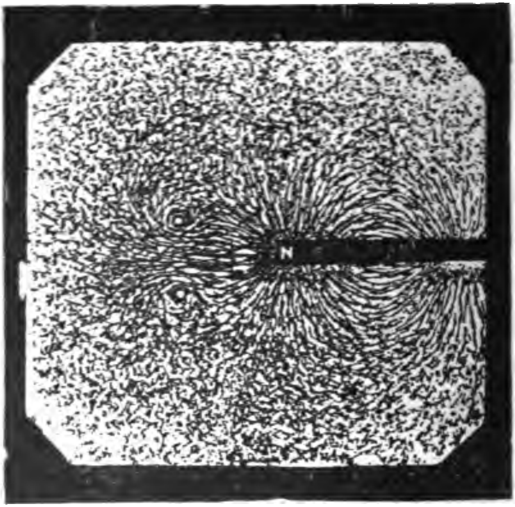
[* *Davis's Manual of Magnetism*, ed. of 1857, pp. 182-3. —H. R. B.]

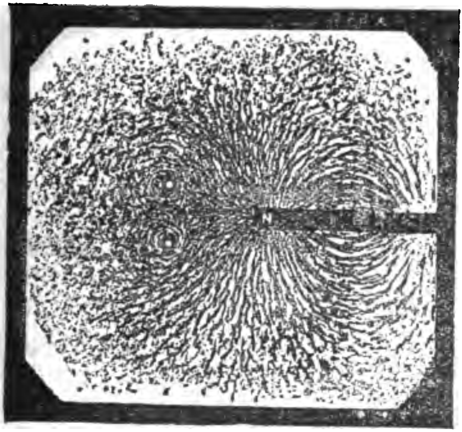
Fig. 49.



POLE OF MAGNET ATTRACTED INTO A CIRCUIT TRAVERSED BY A CURRENT.

plies the answer; for now we find that the magnet's lines of force, instead of being drawn in, are pushed out. In fact, in one case, the pole is attracted, in the other repelled.

Fig. 50.



POLE OF MAGNET REPELLED OUT OF THE CIRCUIT WHEN THE CURRENT IS REVERSED.

Page's suggestion was further developed by Bourbouze, who constructed the curious motor which looks uncommonly like an old type of steam-engine. We have here a beam, a crank, fly-wheel, connecting-rod, and even an eccentric valve-gear and a slide valve. But for cylinders we have four hollow electro-magnets; for pistons we have iron cores, that are alternately sucked in and repelled out; and for slide valve we have a commutator, which, by dragging a pair of platinum-tipped springs over a flat surface made of three pieces of brass separated by two insulating strips of ivory, reverses at every stroke the direction of the currents in the coils of the electro-magnets. It is really a very ingenious machine, but, in point of efficiency, far behind many other electric motors. Unfortunately, it does not do to design dynamo-electric machinery on the same lines as steam-engines.

Yet a fifth class of electric-motors owes its existence to Froment, who, fixing a series of parallel iron bars upon the periphery of a drum, caused them to be attracted, one after the other, by an electro-magnet or electro-magnets, and thus procured a continuous rotation.*

[* Dr. Edmondson, of Baltimore, published in 1834, a description of a rotary motor, which is probably the earliest example of this particular type.—F. L. P.]

Lastly, of the various types of motors we may enumerate a class in which the rotating portion is enclosed in an eccentric frame of iron, so that as it rotates, it gradually approaches nearer. Little motors, working on this principle of "oblique approach," were invented by Wheatstone, and have long been used for spinning Geissler tubes, and other light experimental work. More recently, Trouvé and Weisendanger have sought to embody this principle in motors of more ambitious proportions, but without securing any great advantage.

It would be impossible, within the limits of a lecture, to deal with a tithe of all the various stages of discovery and invention, and if it were my intention to deal with the subject from the historical point of view, I might speak of many interesting and curious machines that have from time to time been tried. I might tell you how Page, after inventing his machine in 1834, succeeded,in 1852, in constructing a motor of such a size that he was able to drive a circular-saw and a lathe by it. I might describe the electric-motor of Davidson, which, in 1842, enabled him to propel a carriage at the speed of four miles an hour, between Edinburgh and Glasgow. I might describe the engine built in 1849, by Soren Hjörth, at Liverpool, which was of ten-horse power.

All these early attempts, however, came to nothing, for two reasons. At that time there was no economical method of generating electric currents known. At that time, moreover, the great physical law of the conservation of energy was not recognized, and its all-important bearings upon the theory of electric machinery were not available.

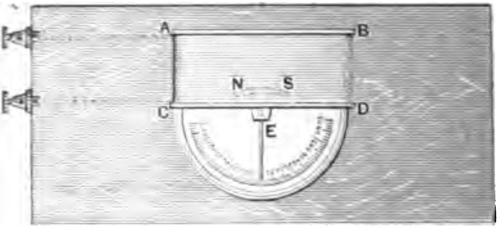
While voltaic batteries were the only available sources of electric currents, economical working of electric-motors was hopeless. For a voltaic battery, wherein electric currents are generated by dissolving zinc in sulphuric acid, is a very expensive source of power. To say nothing of the cost of the acid, the zinc—the very fuel of the battery—costs more than twenty times as much as coal, and is a far worse fuel; for whilst an ounce of zinc will evolve heat to an amount equivalent to 113,000 foot-pounds of work, an ounce of coal will furnish the equivalent of 695,000 foot-pounds.

The fact, however, which seemed most discouraging, and which, if rightly interpreted in accordance with the law of conservation of energy, would have been found to be (on the contrary) a most encouraging fact, was the following:—If a galvanometer was placed in the circuit with the electric-motor and the battery, it was found that when the motor was running it was impossible to force so strong a current through the wires as that which flowed when the motor was standing still. Now there are only two causes that can stop such a current flowing in a circuit; there must be either an obstructive resistance or else a counter-electromotive force. At first, the common idea was that, when the motor was spinning round, it offered a greater resistance to the passage of the electric current than when it stood still. The genius of Jacobi enabled him, however, to discern that the observed diminution of current was really due to the fact that the motor, by the act of spinning round, began to work as a dynamo on its own account, and tended to set up a current in the circuit in the opposite direction to that which was driving it. The faster it rotated the greater was the counter-electromotive force (or "electromotive force of reaction") which was developed. In fact, the theory of conservation of energy requires that such a reaction should exist.

We know that, in the converse case, when we are employing mechanical power to generate currents by rotating a dynamo, directly we begin to generate currents, that is to say, directly we begin to do electric *work*, it immediately becomes much harder work to turn the dynamo than is the case when no electric work is being done. In other words, there is an opposing reaction to the mechanical force which we apply in order to do electric work. An opposing reaction to a mechanical force may be termed a "counter-force." When, on the other hand, we apply (by means of a voltaic battery, for example) an electromotive force to do mechanical work, we find that here again there is an opposing reaction; and an opposing reaction to an electromotive force is a "counter-electromotive force."

The experiment of showing the existence of this counter-electromotive force is a very easy one. All one requires is a little motor, a few cells of battery, and a galvanometer. The galvanometer I shall use to-night is the one which I brought out some years ago, and which has proved itself very convenient for lecture work, because it can be put into any ordinary lantern and projected on the screen (Fig. 51). I have here, as a battery, four small accumulators of the Faure-Sellon-Volckmar type, and I have connected them with a little motor, also of my own design, the current being arranged so as to run through the galvanometer. I hold the spindle of the motor fast, so that it cannot rotate, and you see that the pointer of the galvanometer indicates 44°. I now release the motor; it begins to rotate, and as its speed increases, you observe the needle descends the scale to 23°, and eventually to about 15°. If I load the motor and cause it to slacken speed, the needle at once returns.

Fig. 51



S. P. THOMPSON'S LANTERN GALVANOMETER.

The existence of this counter-electromotive force is of the utmost importance, in considering the action of the dynamo as a motor, because upon the existence and magnitude of this counter-electromotive force, depends the degree to which any given motor enables us to utilize electric energy that is supplied to it in the form of an electric current. In discussing the dynamo as a generator, I pointed out many considerations, the observance of which would tend to improve the efficiency of such generators. It is needless to say that many of these considerations, such as the avoidance of useless resistances, unnecessary iron masses in cores and the like, will also apply to motors. The freer a motor is from such objections, the more efficient will it be. But the efficiency of a motor in utilizing the energy of a current depends not only on its efficiency in itself, but on another consideration, namely, the relation between the electromotive force which it itself generates when rotating, and the electromotive force—or, as some people call it, the electric pressure—at which the current is supplied to it. A motor which itself in running generates only a *low* electromotive force cannot, however well designed, be an *efficient* or economical motor when supplied with currents at a *high* electromotive force. A good low-pressure steam-engine does not become more "efficient" by being supplied with high-pressure steam. Nor can a high-pressure steam-engine, however well constructed, attain a high efficiency when worked with steam at low pressures. Analogous considerations apply to dynamos used as motors. They must be supplied with currents at electromotive forces adapted to them. Even a perfect motor —one without friction or resistance of any kind—cannot give an "efficient" or economical result, if the law of efficiency is not observed in the conditions under which the electric current is supplied to it.

Now it can be shown, mathematically, that the efficiency with which a perfect motor utilizes the electric energy of the current depends upon the ratio between this counter-electromotive force and the electromotive force of the current that is supplied by the battery. No motor ever succeeds in turning into useful work the whole of the currents that feed it, for it is impossible to construct machines without resistance, and whenever resistance is offered to a current, part of the energy of the current is wasted in heating the resisting wire. Let the symbol W stand for the whole electric energy of a current, and let *w* stand for that part of the energy which the motor takes up as useful work from the circuit.* All the rest of the energy of the current, or W—*w*, will be wasted in useless heating of the resistances.

But if we want to work our motor under the conditions of greatest economy, it is clear that we must have as little heat-waste as possible; or, in symbols, *w* must be as nearly as possible equal to W. It can be shown, mathematically, that the ratio between the useful energy thus appropriated and the total energy spent, is equal to the ratio between the counter-electromotive force of the motor and the whole electromotive force of the battery that feeds the motor. The proof will be given later. Let us call this whole electromotive force with which the battery feeds the motor E, and let us call the counter-electromotive force e. Then the rule is

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* This symbol *w* must be clearly understood to refer to the value of the work taken up by the motor, as measured electrically. The whole of this work will not appear as useful mechanical effect, however, for part will be lost by mechanical friction, and part also in the wasteful production of eddy-currents in the moving parts of the motor. What proportion of *w* appears as useful mechanical work depends on the efficiency of the motor *per se*, which we are not here considering. In all that immediately follows we shall suppose such causes of loss not to exist; or the motor will be considered as a perfect motor.

$$w : W = e : E$$

or, if we express the efficiency as a fraction,

$$\frac{w}{W} = \frac{e}{E}.$$

But we may go one stage further. If the resistances of the circuit are constant, the current c, observed when the motor is running, will be less than C, the current while the motor was standing still. But from Ohm's law, we know that

$$c = \frac{E - e}{R},$$

hence

$$\frac{C - c}{C} = \frac{e}{E} = \frac{w}{W}.$$

From which it appears that we can calculate the efficiency at which the motor is working, by observing the ratio between the fall in the strength of the current and the original strength. Now this mathematical law of efficiency has been known for twenty years,* but has been strangely misapprehended. Another law, discovered by Jacobi, not a law of efficiency at all, but a law of maximum work in a given time, has usually been given instead.

Jacobi's law concerning the maximum work of an electric-motor supplied with currents from a source of given electromotive force, is the following:—The mechanical work given out by a motor is a maximum when the motor is geared to run at such a speed that the current is reduced to half the strength that it would have if the motor was stopped. This, of course, implies that the counter-electromotive force of the motor is equal to half the electromotive force furnished by the battery or generator. Now, under these circumstances, only half the energy furnished by the external source is utilized, the other half being wasted in heating the circuit. If Jacobi's law were indeed the law of efficiency, no motor, however perfect in itself, could convert more than 50 per cent. of the electric energy supplied to it into actual work. Now Siemens showed, some years ago, that a dynamo can be, in practice so used as to give out more than 50 per cent. of the energy of the current. It can, in fact, work more efficiently if it be not expected to do its work so quickly.* Dr. Siemens, to whom we owe the honor of having first shown us the true physical signification of the mathematical expressions which, until then, had been regarded as mere abstractions, has in fact proved that if the motor be arranged so as to do its work at less than the maximum rate, by being geared so as to do much less work per revolution, but yet so as to run at a higher speed, it will be more efficient; that is to say, though it does less work, there will also be still less electric energy expended, and the ratio of the useful work done to the energy expended will be nearer unity than before.

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* See Verdet's *Théorie Mécanique de la Chaleur*, where, however, Verdet makes the very mistake so often made, of supposing that the greatest possible efficiency of a motor, working with a given electromotive force, is 50 per cent., or its efficiency when working at the maximum rate.

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* The matter was also very well and clearly put by Prof. W. E. Ayrton, in his lecture on "Electric Transmission of Power," before the British Association in Sheffield, in 1879.

The algebraic reasoning is as follows: If E be the electromotive force of the generator when the motor is at rest, and c be the current which flows at any time, the electric energy W, expended in unit time, will be (as expressed in watts) given by the equation

$$W = Ec = E\frac{(E-e)}{R} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Now, when the motor is running, part of this electric energy is being spent in doing work, and the remainder is wasting itself in heating the wires of the circuit. We have already used the symbol w for the useful work (per second) done by the motor. All the energy which is not thus utilized is wasted in heating the resistances. Let the symbol H represent this heat. Its mechanical value will be HJ, where J stands for Joule's equivalent. Then clearly we shall have

$$W = w + HJ.$$

But, by Joule's law, the heat-waste of the current, whose strength is c running through resistance R, is expressed by the equation

$$HJ = c^2R.$$

Substituting this value above, we get

$$W = w + c^2R \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

which we may also write

$$w = W - c^2R.$$

But by equation (1) $W = Ec$, whence

$$w = Ec - c^2R \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

and, writing for c its value, $\frac{E-e}{R}$, we get

$$w = \frac{(E-e)\,(E-[E-e])}{R}$$

or

$$w = e\frac{E-e}{R} \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Comparing equation (5) with equation (1), we get the following:

$$\frac{w}{W}=\frac{e(E-e)}{E(E-e)}.$$

or, finally, $$\frac{w}{W}=\frac{e}{E}.$$

This is, in fact, the mathematical law of efficiency, so long misunderstood until Siemens showed its significance. We may appropriately call it the law of Siemens. Here the ratio $\frac{w}{W}$ is the measure of the efficiency of the motor, and the equation shows that we may make this efficiency as nearly equal to unity as we please, by letting the motor run so fast that e is very nearly equal to E: which is the true law of efficiency of a perfect motor, supplied with electric energy under the condition of constant external electromotive force.

Now go back to equation (3), which is:

$$w=Ec-c^2R.$$

In order to find what value of c will give us the maximum value for w (which is the work done by the motor in unit time) we must take the differential coefficient and equate it to zero.

$$\frac{dw}{dc}=\mathrm{E}-2c\mathrm{R}=0,$$

whence we have

$$c=\tfrac{1}{2}\frac{\mathrm{E}}{\mathrm{R}}.$$

But, by Ohm's law, $\frac{\mathrm{E}}{\mathrm{R}}$ is the value of the current when the motor stands still. So we see at once, that to get maximum work per second out of our motor, the motor must run at such a speed as to bring down the current to half the value which it would have if the motor were at rest. In fact, we here prove the law of Jacobi for the maximum rate of doing work. But here since

$$c=\frac{\mathrm{E}-e}{\mathrm{R}}=\tfrac{1}{2}\frac{\mathrm{E}}{\mathrm{R}},$$

it follows that

$$\mathrm{E}-e=\tfrac{1}{2}\,\mathrm{E};$$

or

$$\frac{e}{\mathrm{E}}=\tfrac{1}{2},$$

whence it follows also that

$$\frac{\mathrm{W}}{w}=\tfrac{1}{2}.$$

That is to say, the efficiency is but 50 per cent. when the motor does its work at the maximum rate.*

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* It may be worth while to recall a precisely parallel case that occurs in calculating the currents from a voltaic battery. Every one is familiar with the rule for grouping a battery which consists of a given number of cells, viz.: that they will yield a maximum current through a given external resistance when so grouped that the internal resistance of the battery shall, as nearly as possible, equal the external resistance. But this rule, which is true for maximum current (and, therefore, for maximum rate of using up the zincs of one's battery) is not the case of greatest economy. For if external and internal resistance are equal, half the energy of the current will be wasted in heat in the cells, and half only will be available in the external circuit. If we want to get the greatest economy, we should group our cells so as to have an internal resistance much less than the external. We shall not get so strong a current, it is true; and we shall use up our zincs more slowly; but a far greater proportion of the energy will be expended usefully, and a far less proportion will be wasted in heating the battery cells. The maximum economy will, of course, be got by making the external resistance infinitely great as compared with the internal resistance. Then all the energy of the current will be utilized in the external circuit, and none wasted in the battery. But it would take an infinitely long time to get through a finite amount of work in this extreme. The same kind of reasoning is strictly applicable to dynamos used as generators, the resistance of the rotating part of the circuit being the counterpart of the internal resistance of the battery cells. For good economy the resistance of the armature should be very low as com-

Now, though several graphic constructions have been suggested to convey these facts to the eye, none have hitherto been, to my mind, quite satisfactory. I have, therefore, worked out a new construction, which enables me, in one diagram, to exhibit graphically both Jacobi's law of maximum rate of working, and Siemens' law of efficiency.

Let the vertical line, A B (Fig. 52) represent the electromotive force E, of the electric supply. On A B construct a square, A B C D, of which let the diagonal B D be drawn. Now measure out from the point B, along the line B A, the counter electromotive force *e* of the motor. The length of this quantity will increase as the velocity of the motor increases. Let *e* attain the value B F. Let us inquire what the actual current will be, and what the energy of it; also what the work done by the motor is. First complete the construction as follows: Through F draw

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pared with that of the external circuit. Mr. Edison seems to have been struck by this point, as his endeavors to reduce the resistance of his armature coils to the utmost limit of possibility show.

F G H, parallel to B C, and through G draw K G L, parallel to A B. Then the actual electromotive force at work in the machine, and producing the current, is E—e, which may be represented by any one of the lines A F, K G, G H, or L C. Now

Fig.52

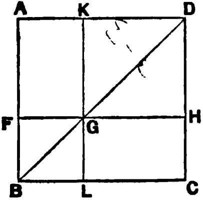
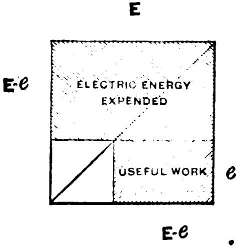


Fig.53



the electric energy expended per second is

$$E\,\frac{(E-e)}{R},$$

and the work done by the motor is

$$e\,\frac{(E-e)}{R}$$

Since R is a constant, the relative values of the two may be written respectively :

$$E\,(E-e)$$

and

$$e\,(E-e).$$

Now

$$\text{area } AFHD = E(E-e),$$

and

$$\text{area } GLCH = e(E-e).$$

The ratio of these two areas on the diagram is the efficiency of the motor.

Let us turn to Fig. 53, in which these areas are shaded. This figure represents a case where the motor is too heavily loaded, and can turn only very slowly, so that the counter-electromotive force e is very small compared with E. Here the area, which represents the energy expended, is very large; while that which represents useful work realized in the motor is very small. The efficiency is obviously very low. Two-thirds or more of the energy is being wasted in heat.

Next, let us turn our attention to the smaller area, G L C H. Obviously, the value of this area will depend upon the position of the point F; for if F is very near B, the area will be very small. If F moves upward, the area, G L C H, will have a value that increases up to a certain point, and then diminishes again; for if F be taken very near A (that is, if e be very nearly equal to E), the area, G L C H, will become again a very narrow strip. Of all the possible cases, the area of this rectangle will be a maximum when G is midway between B and D; for of all possible rectangles that can be inscribed in the triangle, B C D, that rectangle which is a true square will have the greatest value, as drawn in Fig. 54. But if G is midway between B and D, the rectangle, G L C H, will be exactly half the area of the upper rectangle, A F H D; which is, in fact, Jacobi's law of the efficiency of a motor doing its work at its greatest possible rate. Also F will be half way between B and A, which signifies that $e = \frac{1}{2}$ E.

Again, consider these two rectangles when the point G moves indefinitely near to D (Fig. 55). We know, from Euclid's Second Book, familiar from our school-days, that the rectangle, G L C H, is equal to the rectangle, A F G K. The area (square), K G H D, which is the excess of A F H D, over A F G K, must, therefore, represent that part of the electric energy which is wasted in heating the resistance of the motor and circuit. In Fig. 53 this corner square, which stands for the heat-waste, was enormous. In Fig. 54 it was exactly half the energy. In Fig. 55 it is only about one-eighth. Clearly, we may make the heat-waste as small as we please, if only we will take the point F very near to A. The efficiency will be a maximum when the heat-waste is a minimum. The ratio of the areas, G L C H and A F H D, which represents the efficiency, can only become equal to unity when the square, K G H D, becomes indefinitely small; that

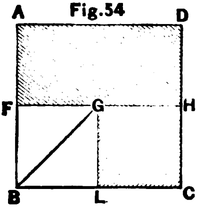


Fig.54

Geometric illustration Jacobi's law of maximum rate of doing work.

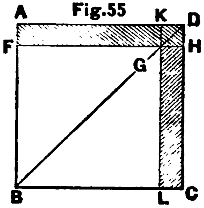


Fig.55

Geometric illustration Siemens's law of efficiency.

is, when the motor runs so fast that its counter-electromotive force, *e*, differs from E by an indefinitely small quantity only. Further, it is clear that if our diagram is to represent any given efficiency—for example, an efficiency of 90 per cent., then the point, G, must be taken so that the area G L C H = 9-10ths of the area A F H D; or G must be 9-10ths of the whole distance along B D. This involves that *e* shall be equal to 9-10ths of E, or that the motor shall run so fast as to reduce the current to 1-10th of what it would be if the motor were standing still. Thus we verify, geometrically, Siemens' law of efficiency.*

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* We have all along supposed the motor to be a 'perfect" one, that is to say, one which gave out as available mechanical work all the electric work it took from the supply of energy of the current. No motor does this, because of friction, &c. But it is easy to adapt the construction to the case. Suppose when working the motor as a generator, so as to give an electromotive force *e*, we found that it was capable of converting 80 per cent of mechanical energy into electrical energy; then we may put down the efficiency of the motor, *per se*, under the given conditions at 80 per cent. All we have, then, to do, is to take an area 8-10ths of the size of the area G L C H (or cut off 1-5th of G L C H), and this will really represent the available mechanical work of the motor.

In all the preceding discussion, I have supposed that the motor is to be worked with a supply of current furnished at a fixed electromotive force. It is not only convenient, but I believe wise, to make such a condition the basis of the argument, because this is probably the condition under which electric power will, in the not very distant future, be distributed over large areas. It would be absurd, in the present stage of electro-technical science, to deal with such a question as the construction and use of motors, without taking into account the practical conditions under which they will be used. It is true that the condition of having a constant fixed electromotive force is not the only condition of supply; for, as we have seen in preceding lectures, a generator or system of generators may be worked so as to yield a constant current. And it would be quite possible to formulate a set of rules for the efficiency and maximum duty of motors under this condition. But this method of distributing electric power is far less likely to be of importance in the near future than the system of distribution with constant electromotive force; though for the case of transmission of power to an isolated station, the case becomes of importance. One simple problem connected with this case is worthy of mention. Suppose that one is desirous of working a motor, so as to do work at the rate of a specified number of horse-power, and that the wire available to bring the current cannot safely stand more than a certain current, without being in danger of becoming unduly heated. It might be desirable to know what electromotive force such a motor ought to be capable of giving back, and what electromotive force must be applied at the transmitting end of the wire. Let N stand for the number of horse-power to be transmitted, and c for the maximum strength of current that the wire will stand (expressed in ampères.) Then, by the known rule for the work of of a current, since—

$$\frac{ec}{746}=\mathrm{N},$$

$$e = \frac{746\,\mathrm{N}}{c},$$

gives the condition as to what electromotive force the machine must be capable of giving, when running at the speed it is eventually to run at as a motor. Moreover, the primary electromotive force, E, must be such that

$$\frac{\mathrm{E} - e}{\Sigma\mathrm{R}} = c$$

where $\Sigma\mathrm{R}$ is the sum of all the resistances in the circuit. Whence,

$$\mathrm{E} = e + c\Sigma\mathrm{R}$$

which is the required condition.

Another problem in the application of motors to transmission of power, which vitally affects their construction, is the determination of the relation of the heat-waste to the electromotive force at which the current is supplied to the motor.

If, as before, $\Sigma\mathrm{R}$ stands for the sum of all the resistances in the circuit, then, by Joule's law, the heat-waste is (in mechanical measure)

$$\mathrm{HJ} = \mathrm{C}^2\Sigma\mathrm{R}.$$

And, since $c=\frac{E-e}{\Sigma R}$ we may write the heat-waste as

$$HJ=\frac{(E-e)^2}{\Sigma R}.$$

Now suppose that without changing the resistances of the circuit we can increase E, and also increase e, while keeping E—e the same as before, it is clear that the heat loss will be precisely the same as before. But how about the work done? Let the two new values be respectively E' and e'. Then the electric energy expended is—

$$W'=\frac{E'(E'-e')}{\Sigma R},$$

and the useful work done is—

$$w'=\frac{e'(E'-e')}{\Sigma R}.$$

That is to say, with the no greater loss in heating, more energy is transmitted, and more work done. Also the efficiency is greater, for

$$\frac{w'}{W'}=\frac{e'}{E'},$$

and this ratio is more nearly equal to unity than $\frac{e}{E}$ because both E and e have received an increment arithmetically equal. Clearly, then, it is an economy to work at high electromotive force. The importance of this matter, first pointed out by Siemens, and later by Marcel Deprez, cannot be overrated. But how shall we obtain this higher electromotive force? One very simple expedient is that of driving both the generator and motor at higher speeds. Another way is to wind the armatures of both machines with many coils of wire having many turns. This expedient has, however, the effect of putting great resistances into the circuit. This circumstance may, nevertheless, be no great drawback, if there is already a great resistance in the circuit—as, for example, the resistance of many miles of wire through which the power is to be transmitted in this case; doubling the electromotive force will not double the resistance. Even in the case where the line resistance is insignificant, an economy is effected by raising the electromotive force. For, as may be deduced from the equations, when E—e is kept constant, the effect of doubling the electromotive force is to double the efficiency when the resistance of the line is very small as compared with that of the machines, and to quadruple it when the resistance of the line is very great as compared with that of the machines. It is, in fact, worth while to put up with the extra resistance, which we cannot avoid if we try to secure high electromotive force by the use of coils of fine wire of many turns. It is true that the useful effect falls off, *cœteris paribus*, as the resistance increases: but this is much more than counter-balanced by the fact that the useful effect increases in proportion to the square of the electromotive force.

In the recent attempt of M. Marcel Deprez to realize these conditions, in the transmission of power from Miesbach to Munich through a double line of telegraph wire, over a distance of thirty-four miles, very high electromotive forces were actually employed. The machines were two ordinary Gramme dynamos, similar to one another, but their usual low-resistance coils had been replaced by coils of very fine wire. The resistance of each machine was consequently 470 ohms, whilst that of the line was 950 ohms.* The velocity of the generator was 2,100 revolutions per minute; that of the motor 1,400. The difference of potential at the terminals of the generator was 2,400 volts; at that of the motor 1,600 volts. According to Professor von Beetz, the President of the Munich Exhibition, where the trial was made, the mechanical efficiency was found to be 32 per cent. M. Deprez has given the rule that the efficiency $\frac{w}{W}$ is obtained, in the case where two identical machines are employed, by comparing the two velocities at the two stations. Or

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* These figures, and those which follow, are given on the authority of the President of the Munich Exhibition, Professor von Beetz. It is but fair to add that M. Deprez is not satisfied of their accuracy.

$$\frac{w}{W}=\frac{n}{N}$$

where N is the speed of the generator, n that of the motor. There is, however, the objection to this formula, that the electromotive forces are not proportional to the speeds unless the magnetic fields of the two machines are also equally intense, and the current running through each machine the same. This is not the case if there is leakage along the line. Moreover, when there are resistances in the line, the ratio of the two electromotive forces of the machines is not the same as the ratio of the two differences of potentials, as measured between the terminals of the machines.

I now turn back from these somewhat abstract questions, to consider by the light we have already derived, some points in the design and construction of motors. We shall find that many of the rules suggested in my former lecture are applicable also to the case of motors, and supply answers to many of the questions that naturally arise.

In the first place, shall we build motors large, or shall we build numbers of small ones? In my first lecture I proved that, in the dynamo used as a generator, the capacity for doing work increased as the fifth power of the linear dimensions; that by doubling a dynamo in length, breadth,and thickness, we had a machine weighing eight times as much, costing less than eight times as much, but capable of doing thirty-two times the work, and that with a great gain in economy in working. The same thing is true of motors. Suppose instead of building eight small motors, we build one large one, of doubled dimensions. It will not cost so much as the eight, will get through four times as much work as the eight put together, and will be more economical in working. I assume here, of course, that the large machine can be placed under equally advantageous conditions of supply.

This is by no means the only one of the points in the theory of the dynamo which can be applied to practice in the cases in which the dynamo is used as a motor. I will give another example.

In the prospect of an immediate field of usefulness opening out for motors, so soon as we have such a thing as regular town supplies of electric currents laid on, it is most important that motors should be designed, not simply to work with the constant electromotive force supplied at the electric mains, but designed also to work at uniform speeds. It is highly important for example in driving a lathe, and indeed, many kinds of machinery, that the speed should be regular, and the motor should not "run away" as soon as the stress of the cutting tool is removed. Now, in my second lecture, I spent some time explaining the methods by which M. Marcel Deprez and Professor Perry had solved a converse problem to this, namely, that of getting a dynamo to feed a circuit with currents at a constant electromotive force, when driven with a uniform speed. The solution to that problem we saw consisted in using certain combinations for the field magnets which gave an initial magnetic field, independently of the actual current furnished by the dynamo itself. Now, it is not hard to see that this problem may be applied conversely, and that motors may be built with a combination of arrangements for their field magnets, such that when supplied with currents at a certain constant electromotive force, their speed shall be constant, whatever the work or no work which they may be doing. The one difficulty in the problem—and this is a mere matter for experiment and calculation—is to find the critical number of volts of electromotive force at which this will hold good, It is, in fact, the converse to the operation of finding the critical velocity at which one of Deprez's or of Perry's combination dynamos must be driven, in order that it may give a constant electromotive force. M. Marcel Deprez has, himself, constructed motors upon this plan. Some three years ago, I saw one of Deprez's motors, which ran at a perfectly uniform speed, quite irrespective of the work it was doing. Whether it was lifting a load of five kilogrammes from the ground, or was letting this load run down to the ground, or ran without any load at all, the speed was the same. At the Paris Exposition Electrique of 1881, a large number of Deprez's motors were shown, running at uniform speed and driving various machines, lathes, sewing-machines, &c.

Amongst others who have aimed at producing a motor to work at uniform speed, are Professors Ayrton and Perry. Professor Ayrton informs me that one of these motors, weighing only 350 pounds, will give an effective power equal to 8-horse power, and that "without any mechanical governor; without anything, in fact, in the nature of a moving governor, it always goes at the same speed, whatever work it has to do." Certain little legal matters connected with the protection of this invention have debarred Professor Ayrton from informing me more fully of the new machine, which, if it fulfils the promise of its inventors, will be a great step forward in the mechanical application of electricity. But I can hazard a guess that the arrangement for obtaining uniform speed is dependent on the prior condition that the motor be supplied, either with a constant electromotive force, or with a constant current of a certain "critical" value; and that the solution of the problem is virtually one of the cases of combination, the counterpart of which, as applied to generators, I discussed last week.

It is, of course, possible to use as a motor any direct current dynamo, whether the field-magnets be series-wound, shunt-wound, separately excited, or permanently magnetized. There is this curious point of difference in different cases. Suppose the dynamo to be arranged so as to work as a generator, and then to be supplied with currents from an exterior source, to make it work as a motor. If the dynamo is series-wound, it will run the reverse way (or against its brushes), no matter which way the currents run through it. If the dynamo be shunt-wound, it will run with its brushes, whichever direction the current runs through it. The direction of rotation taken by the separately excited and the magneto-machine will also be with the brushes, if the current is in the right direction, through the armature. These points have to be taken into account in any attempt to combine the different systems.

If we attempt to apply to motors rules and suggestions, such as those applied to generators in the first of these lectures, we shall find that while some of them apply directly, others are singularly in contrast. For example, we found it advisable, for the sake of steadying the currents in generators, to use large and long field-magnets with plenty of iron, and with heavy pole pieces. In the case of motors, there is no such necessity laid upon us; for we want here to produce a uniform steady rotation. Now, even if the impulses be intermittent, the mechanical inertia of the moving parts will steady the motion. Electric curents have no such inertia (except in so far as the self-induction in a circuit exerts an influence like that of inertia), and hence the precautions for generators. In the case of generators, we found that, to produce steady currents we had to multiply coils on the armature in many separate paths grouped round a ring or a drum, involving a complicated winding, and a collecting apparatus consisting of many segments. In motors no such necessity exists, provided only we arrange the coils that there shall be no dead points. I do not say that for large motors, it may not be advisable to multiply the paths and segments for other reasons—as, for example, to obviate sparking at the collectors—but for securing steady running, the inertia of the moving parts spares us—at any rate, in small machines—the complication of parts which was expedient in the generator. Some of the most successful of the little motors that have recently appeared—those, for example, of Deprez, Trouvé, and Griscom*—have for their armatures the simple old shuttle-wound Siemens armature of 1856, and in these motors, of course, there is the disadvantage of dead-points to take into account. Deprez, in his first motors, placed this armature longitudinally between the poles of a horse-shoe magnet, with the axis parallel to the limbs. He has also constructed motors with two such armatures on one spindle, one of the coils being 90° in advance of the other, so that while one was at the dead point the other should be in full action. The same suggestion has been carried out in Akestor's motor. Trouvé has tried to get over the dead-points, by utilizing the method of oblique approach mentioned earlier in my lecture. The Griscom motor, which has little cop-

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[* U. S. patent, No. 227,622, May 18, 1880.—H. R. B.]

per rollers as commutator brushes, has, for its field-magnet, a compact tubular electro-magnet wound in series with the armature. It has the disadvantage of dead-points. There is, in all these motors, the disadvantage that at every half-revolution the magnetism of the armature core is reversed; and as in all these forms this core is of solid iron, there must be waste by heating in the cores. In fact, to the rotating armatures of motors, as to those of generators, apply all the rules about slitting to get rid of induced eddy-currents, avoiding idle coils and useless resistances, &c. The rules about proper pole-pieces, adjustable brushes, multiplication of contacts, also are mostly applicable to motors as well as to generators.

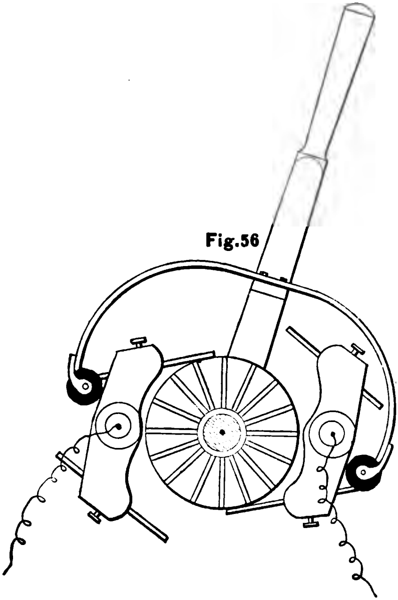
In order to meet the case of a handy and reliable motor, I have designed a machine, the smallest size of which is on the table before you. The field-magnets, which also constitute the bed-plate of the motor, are of malleable cast iron, of a form that can be cast in one, or at most two pieces. The form of them is that of a Joule's magnet, with large pole-pieces, and wound with coils, arranged partly in series, partly as a shunt, in certain proportions, so as to give me a constant velocity when worked with an external electromotive force of a certain number of volts.

As an armature, I employ a form which, I think, unites simplicity with efficiency for the end desired. I do not want dead points, and yet I do not want to have a complicated armature. I have, therefore, modified the old Siemens armature by embedding, as it were, one of the shuttle-shaped coils within another at right angles and having duplicated the coils, I must of course duplicate the segments of the commutator, which therefore becomes either a four-part collector, or else a double collar, according to circumstances. There are no solid iron parts in the armature, but the cores are made of thin pieces of sheet iron, stamped out and strung together. Of the efficiency of this little motor you were witnesses a little while ago, when I employed it in the experiment with the galvanometer.

There are here on the table two other forms of motor, one of which is the design of Mr. A. Reckenzaun, C.E., and which is interesting, because its armature though a drum-armature in form, in reality consists of independent coils, connected, like those of the Brush dynamo, to separate commutators. There are, in fact, four commutators grouped as two twos, and the two pairs of brushes in contact with them.

The other motor is one of the pattern invented by De Meritens, who employs a ring-armature very like that of Gramme, but places it between very compact and light field-magnets, which form a framework to the machine. There is one point about this machine of great interest, which is, however, a later addition. It is provided with a reversing gear, which, when I move the handle, reverses the direction in which it runs. This gear, which is the invention of Mr. Reckenzaun (to whom I am indebted for the loan of this motor) is shown in Fig. 56.* In it there are two pairs of brushes; the

Fig.56



RECKENZAUN'S REVERSING GEAR.

[* A reversing gear for electric locomotives constructed in the same manner, viz.: with two pairs of brushes giving a lead in either direction has been patented by Stephen D. Field, No. 232,253, of Sept. 14, 1880.—H. R. B.]

two upper are fixed to a common brush-holder, which turns on a pivot, and can be tilted by pressing a lever handle to right or to left. The two lower brushes are also fixed to a holder. Against each brush-holder presses a little ebonite roller, at the end of a bent steel spring, fixed at its middle to the handle. The result of this arrangement is that, by moving the lever, the brushes can be made to give a lead in either direction, and so starting the motor rotating in either direction. Such a reversing gear is obviously a most essential adjunct for industrial applications of motors, and, if the difficulties of sparking at the brushes, caused by the sudden removals of them from the collector, be obviated, must prove much better than any mechanical device to reverse the motion, by transferring it from the axle of the motor through a train of gearing to some other axle. One great advantage of electric motors is, that they can be so easily fixed directly on the spindle of the machine they are to drive; an advantage not lightly to be thrown away.

There is, indeed, an immense field for useful industrial application of the electric motors, so soon as we once have at our disposal regular town-supplies of electric currents. Already we have got the little motors of Griscom, Howe, and others, adapted to work sewing-machines, and instruments requiring very small power. Larger motors for driving lathes and heavier machinery, though not yet much known to the public, are in the market. Messrs. Siemens have brought out an electric lift or elevator,* in which a small dynamo, itself running very quickly, drives an endless screw, and communicates a slow but powerful motion to a drum on which the hauling chain is wound. If town-supplies of electricity were accomplished facts, such lifts would be multiplied. Indeed, there very many purposes for which hydraulic power is used, in which electric power might be advantageously substituted. The electric railway, dimly foreshadowed by George Little in 1844, when he patented an "electromotive," has become an established fact. From the electric railway first established in Berlin in 1880, by Siemens and Halske, we already have had the further developments of the electric tramway in Paris, and the experimental electric railway at the Crystal Palace. Edison has constructed an electric railway at Menlo Park, and built electric locomotives to ply upon it. Nor must I omit to mention how, in the bleaching fields of France, an electric tramway does most satisfactory duty; nor how, finally, in the sister isle, at the Giant's Causeway, Messrs. Siemens Brothers have estab- a line of electric railway, which is now actually in operation.

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* Dr. Hopkinson has also invented an electric lift, in which the armature of the motor, running at a high speed, works the chain of the lift by a train of toothed wheels, which reduce the speed. This elevator was shown in operation at the Paris Exposition of 1881.

Latest of all the applications of the dynamo as a motor is that of electric navigation. Jacobi, as we know, fitted up, in 1838, an electric paddle-boat, which he propelled on the Neva, first with Daniell's and afterwards with

Grove's cells, and was very able, when he used 128 large cells, to carry fourteen persons against the stream, at a speed of about 1¼ miles per hour.

M. Trouvé, of Paris, was the next to apply electric power, in the shape of Planté's accumulators, to a pleasure-boat, with which he navigated the Seine. But M. Trouvé has more recently abandoned storage cells, and has returned to the use of a bichromate battery, wherewith to drive the little boats, which he fits up with his little motors, mounted upon the top of the rudder, and turning a light screw-propeller by a driving belt, which passes down behind the rudder into the water.

Still more recent is the electric launch which made its trial trip on the Thames,* last September. This is an iron boat twenty-five feet long, fitted with a screw, and able to carry twelve persons, while running against the tide, at a pace of eight miles an hour. No existing motor of requisite power having yet been made of a form convenient to place directly upon the axis of the propeller, the expedient has, in this case, been resorted to of driving the screw by belts from an overhead counter shaft, which receives its motion from two small Siemen's dynamos placed below. The arrangements of the machinery of the boat are depicted in Fig. 57. Each of these dynamos has been provided by Mr. Reckenzaun, who designed the fittings of the launch, with reversing gear like that shown in Fig. 56. The current, which actuates these dynamos, is derived from forty-five accumulators of the Sellon-Volckmar type, which are charged while the launch lies at its moorings. Though this is a great step in electric navigation, I venture to believe that it is yet but a beginning of greater things. As with steamboats so with electric-boats,

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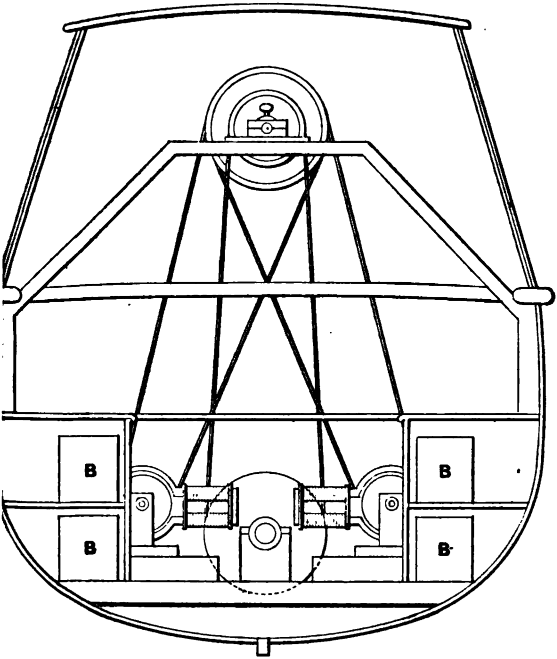
* In 1856, Mr. G. E. Dering constructed, at Messrs. Searle's, an electric boat worked by a motor, in which the rotation was effected by magnets arranged within coils, like galvanometer needles, and acted on successively by currents from a battery. It succeeded, I am informed, in making headway, though at small speed, against the tide at its swiftest.

Fig.57



MACHINERY OF THE LAUNCH "ELECTRICITY."

we shall find that we begin with small experimental attempts, and increase in size as experience dictates. It is but a few days since I was reading, in an old volume of the *Philosophical Magazine* for the year 1801, of Symington's early little steamboat—the forerunner both of Fulton's and of Bell's—and the writer of the article hardly dared to think of this as more than an ingenious experiment, and doubted whether large vessels could ever be practically driven by steam. When I read this curious narrative, I bethought me of the trial trip of the little launch *Electricity*, and began to think that I was not so very hopelessly wrong, when I wrote in September last: "Who shall say to what proportions this latest application may not attain in the next decade?"* Could we look forward, and see with our eyes to-night the electric boats of fifty years hence, we should not, perhaps, be more surprised than those who beheld the first rude steamboat would be, if they could now rise from their graves to behold the great ocean-going steamships of to-day. Indeed, when I look around, and see so many opportunities for the future application of electric motive power; so many instances in which the dynamo would supply a welcome and economical† means of doing that which is now done by less advantageous means, I begin to wonder why we do not establish central supplies of electric currents for this purpose, which is surely as important as electric lighting. Here we have the possibility of introducing machinery that is portable

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* It is well known that a no less authority than Dr Lardner publicly pronounced it impossible for any steamboat every to carry coals enough to enable her to cross the Atlantic. It is also recorded that a very eminent public man offered to swallow the boilers of the first steamboat that should succeed in crossing the Atlantic. But he would be a bold man who would now-a-days promise to swallow the accumulators or the dynamos of the first electric boat that shall successfully make the same trip across the water.

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† As to the economy of electric motive power, I may perhaps be allowed to quote a passage from a recent lecture of my own in Bristol, in which a concrete case is presented: "When it is possible thus to obtain power by merely turning on a tap, there will be an enormous impetus to all kinds of small machinery. Motors to work sewing-machines already exist, and would be used literally by millions if the source of electricity were but at hand, in the form of a friendly wire always ready to bring the needed power. . . . Again, the establishment of a town supply of electricity will tend unquestionably to develop the industries of small workshops and home workshops, where a little power is required. I have already explained how, with steam power, small engines of one horse-power or less are uneconomical. But with electricity it is not so. The smallest electro-motors may be made just as economical as are the largest. There is, moreover, another point in their favor. They may be

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made far smaller, lighter, more compact, and far cheaper than steam-engines of corresponding power. . . . It is certainly possible to construct an electric motor of two horse-power for ten pounds, and such a motor would be ample for the purposes of many small workshops. Why do we not, it may be asked, hear and see more of these little machines, if they are so excellent? Why do not people adopt them? The answer is simply they cannot be used until we have a central supply of electricity. I do not hesitate to affirm that such motors will be found to present an enormous economy in comparison with steam-engines of equal power. Take the case of a small workshop which wants just two horse-power to turn a few lathes or drilling machines. A small steam-engine and boiler will, together, cost about £70 ($350), and the consumption of coal will be about 13 lbs. weight per hour. Instead of this, put in a motor costing, let us say, £20 ($100), which allows for handsome profits on manufacture. Here is a saving in capital outlay at once. Moreover, the motor may be put right into the workshop, for it is small—perhaps two feet long, eighteen inches broad, and one foot high—and is not liable to leak or explode. The next point to consider is the cost of running it. Let us suppose that it has only an efficiency of 70 per cent., or that it only turns 7-10ths of the energy of the current into useful mechanical work.

and light, giving out power without the inconveniences and risks hitherto attending the employment of power. Surely there must be many workshops in every town where the owner would be glad of having power without the trouble and danger of a furnace, boiler, and steam-

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(Many motors will do far more than this.) Let us also suppose that the currents are furnished by a dynamo whose efficiency is 90 per cent. (which figure is also capable of being attained in practice), worked by a large central steam-engine, consuming only 1½ lbs. of coal per horse-power. Allow 4 per cent. for loss, by resistance, in the conducting cables; this reduces the total efficiency of the generator to 86 per cent., and of that 86 per cent. only 7-10ths—*i. e.*, 60.2 per cent — is eventually converted back into useful work by the motor. We have, then, 40 per cent. wasted in order to get 60 per cent. of useful work. How does this affect the coal consumption for two horse-power? At the central station 3 lbs. of coal per hour would suffice were there no loss in conversion into electric energy, and back again into mechanical power. As it is, 5 lbs. of coal per horse-power, will be needed, 3 lbs. of which represent the 60 per cent. of useful power transmitted, and 2 lbs. to represent the 40 per cent. wasted. In practice I believe, a far less margin of waste might be looked for. Yet even with this large waste there is still an immense economy effected, for we get our two horse-power by an expenditure of 5 lbs. of coal at the central station, instead of 13 lbs. of coal in the furnace of a small steam-engine. It is clear, then, that electricity offers an enormous future to small motor machinery."